Airspeed estimation using GPS with Improved accuracy

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Introduction:

The velocity for an airplane in the conventional way is calculated using a pitot tube. A pitot-static system is a system of pressure-sensitive instruments that is most often used in aviation to determine an aircraft's airspeed and altitude. It consists of a pitot tube, a static port, and the pitot-static instruments. This equipment is used to measure atmospheric parameters and calculate velocity as a function of the temperature, density and the pressure of the fluid in which it is operating.

The fact that all these vary on a large scale based on atmospheric conditions and particle nature, errors are prone to occur. The principle used in the calculation is Bernoulli's principle which is only valid for incompressible flows i.e. density along the fluid has to be constant which is only under the speed of Mach 0.3 whereas the modern commercial jets fly at 0.78M. In the past, several airline disasters have been traced to a failure of the pitot-static system. In the proposed system effort has been made to make the value accurate and can be used as a reliable replacement in case of failures or weather uncertainties.

Abbreviations Used

- GPS Global positioning system
- GS Ground Speed
- AS Air speed
- WS Wind speed
- TAS True airspeed
- IAS Indicated airspeed
- EAS Equivalent airspeed
- NGS New ground speed
- NEAS New equivalent airspeed
- TAT Total air temperature
- AL Altitude
- DEG Decimal coordinates in degrees
- RAD Decimal coordinates in Radians

- Lat1 Latitude 1
- Lon1 Longitude 1
- Lat2 Latitude 2
- Lon2 Longitude 2

Pitot - static tube

A mechanical instrument used to determine the indicated airspeed of aircraft. It gives instantaneous speed of the aircraft at any point of time by using Bernoulli's principle.

Common Errors:

1. Density errors: Density errors affect instruments metering airspeed. This type of error is caused by variations of pressure and temperature in the atmosphere.

2. Compressibility errors: A compressibility error can arise because the impact pressure will cause the air to compress in the pitot tube.

3. Hysteresis: Hysteresis errors are caused by mechanical properties of the aneroid capsules located within the instruments. These capsules, used to determine pressure differences, have physical properties that resist change by retaining a given shape, even though the external forces may have changed.

These errors are likely to occur even after frequent maintenance and instrumentation checks.

The proposed system could serve as a replacement to the conventional pitot tube in calculating velocity, eliminating many of the errors mentioned above. It is a zero-maintenance system with improved accuracy because of its relative independence on the ever-changing atmospheric conditions.

GPS is very accurate and the fastest method of locating anything on the planet with accuracy at an arm's length. The algorithm makes effective use of this existing technology in aircraft to determine the real-time velocity using data feed given from altimeter.

First step to improving accuracy of the ground speed relative to true airspeed:

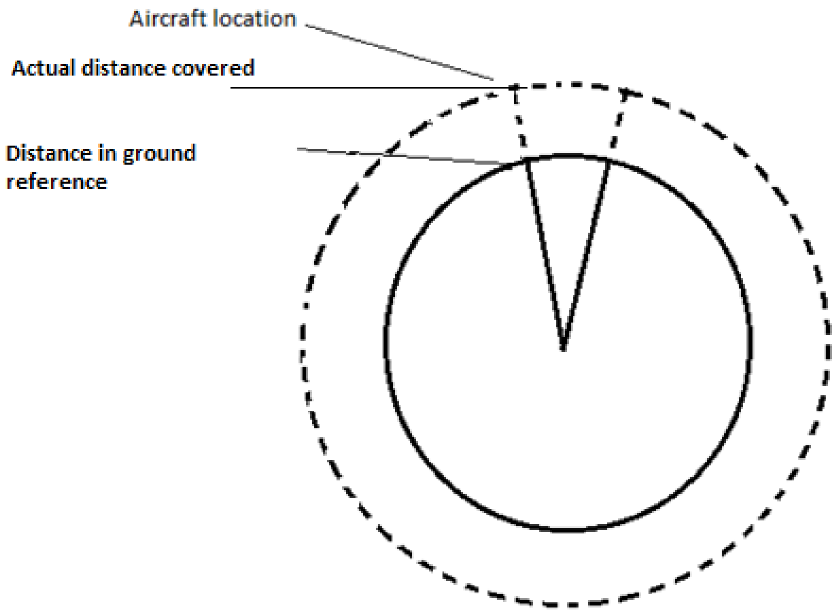
The current GPS system is in reference to the latitudes and longitudes taken on the ground, but an aircraft moves at high altitudes. If we imagine this altitude added to radius of earth to be the new radius of an imaginary sphere then we can say that the sphere has larger surface area than earth.

So if the distance between two points on earth is 100km and an airplane takes 1hr to cover it then the plane actually covered a distance >100km in that hour depending on the altitude it travelled in, making the speed of the airplane > 100km/hr.

This relative error can be compensated by adding a simple transformation ratio calculated between the square root of the surface area of earth and the imaginary sphere.

Traditionally speed is the ratio of distance travelled to the time taken by a body. We employ the same method for the calculation of speed of any aircraft. Until now the GPS employed in an aircraft is used to let the pilot know the aircraft's location based on ground reference.

The new system enables us to improve accuracy and calculate a more accurate velocity of the aircraft.



The diagram is not scaled to show the clear difference in the distance due to change in altitude. The actual error isn't that big but it is significant.

Aircraft speed can be divided into its components as horizontal velocity and vertical velocity

Existing algorithm for Horizontal velocity:

The horizontal velocity can be obtained by knowing the latitude and longitude of two points and the time taken by the aircraft between two such points.

The algorithm for calculating the horizontal velocity is as follows:

```
double distance(double latitude1, double longitude1, double latitude2, double
longitude2, double height)
 {
        // Converting degrees to radians
        //M_PI 3.14159265358979323846

        latitude1 = latitude1 * M_PI / 180.0;
        longitude1 = longitude1 * M_PI / 180.0;
        latitude2 = latitude2 * M_PI / 180.0;
        longitude2 = longitude2 * M_PI / 180.0;

        // radius of earth in meters
        double r = 6378100;

        // Position vector 1
        double rho1 = r * cos(latitude1);
        double z1 = r * sin(latitude1);
        double x1 = rho1 * cos(longitude1);
        double y1 = rho1 * sin(longitude1);

        // Position vector 2
        double rho2 = r * cos(latitude2);
        double z2 = r * sin(latitude2);
        double x2 = rho2 * cos(longitude2);
        double y2 = rho2 * sin(longitude2);

        // Dot product of both position vectors
        double dot = (x1 * x2 + y1 * y2 + z1 * z2);
        double cos_theta = dot / (r * r);

//Obtaining theta by applying inverse cosine
        double theta = acos(cos_theta);
```

Ratio calculation for accuracy improvement:

To improve the accuracy, we use this extra part which includes the ratio difference of the distance traveled between ground perspective and the imaginary sphere.

```
        //The ratio between ground distance and actual distance
         double r = 63718100;
         double surf1 = 4 * 3.14159265358979323846 * r * r
         double surf2 = 4 * 3.14159265358979323846 * (r+h) * (r+h)
         double ratio = surf2/surf1

        // Distance in Meters is a function of theta and radius of earth and ratio
        return r * theta * square root (ratio);
}
```

Now once you have the distance between the points in the air you can calculate the velocity by dividing this distance by time taken between the two position measurements like this:

auto final-distance = distance(p1.latitude, p1.longitude, p2.latitude, p2.longitude);
auto time = (p2.timestamp - p1.timestamp) / 1000.0;
double horizontal velocity = final-distance / time;

Explanation of the algorithm:

We get the horizontal velocity by converting the latitude and longitude values obtained from GPS of two points and converting them to position vectors on the geoid. First, we translate latitude/longitude to a position vector in three dimensions. Project the point 1 onto the equatorial plane (xy - plane) using *ρ = r cos(latitude1)*, where r is the radius of the earth. The z-coordinate of point 1 is *r sin(latitude1)*. The x-coordinate is *ρ cos(longitude1) = r cos(latitude1) cos(longitude1)*, and the y-coordinate is *ρ sin(longitude1) = r cos(latitude1)sin(longitude1)*. Repeat this procedure for the other point 2. We end up with two position vectors.

The great circle distance between two points 1 and 2 on the earth's surface is *r * θ*, where r is the radius of the earth and θ is the angle between the position vectors. θ is the central angle between the vectors at the earth's center. We get the angle θ by the "dot product" of the two position vectors. Once we have θ by this method, then the arc distance between two points on earth's surface is r * θ. But because aircraft's fly at an altitude, we need to create an imaginary sphere with a radius of r+h, then we find the square root of ratio between surface area of earth to that of the sphere. Multiplying this ratio with the distance we obtained will give us the actual distance travelled by the airplane. Hence final distance would be *r * θ * sqrt(ratio).*

Now that we have distance and timestamps we can calculate the velocity by dividing this distance by time taken between the two position measurements.

Second step to improving accuracy of the ground speed relative to true airspeed:

Vertical Velocity

An aircraft also has vertical movement which is to be considered to find the total velocity of an aircraft, to accommodate that we calculate vertical velocity. Vertical velocity is the rate of change of altitude. To obtain accurate speed in situations like aircraft takeoff, landing and many other cases where the aircraft isn't necessarily moving in horizontal direction, we calculate the vertical velocity and find total velocity through vector addition of both vertical and horizontal velocities.

Vertical velocity is the rate of change of altitude, which is:

$V_h = dh/dt = |h_1 – h_2| / |t_2 - t_1|$

Aircraft's new Ground speed is now determined by using vector addition,

$V = \sqrt{(Vh^2 + Vv^2)}$

True Airspeed and Ground speed relation in an aircraft at different altitudes:

The true airspeed of an aircraft is the actual speed relative to the airmass in which it is flying. True airspeed is not used for controlling the aircraft during taxiing, takeoff, climb, descent, approach or landing for these purposes the Indicated airspeed IAS or KIAS is used.

However, since indicated airspeed only shows true speed through the air at standard sea level pressure and temperature, TAS is necessary for navigation purposes at cruising altitude in less dense air.

Now using the above-mentioned corrections, the new Ground speed "V" is brought closer to the True airspeed of the aircraft leaving the difference between GS - TAS = WS (wind speed) being more accurate now. The importance of wind speed is for knowing the relative speed of the aircraft with the medium for navigation and position of the aircraft with respect to ground in low density conditions.

Calculating the EAS using ground speed:

We know that GS is calculated using GPS and the velocity is calculated independent of any external parameters purely taking the distance traveled by the aircraft between time-stamps.

If we apply the density ratio relation between TAS and EAS (equivalent air speed) to GS we will get a new velocity which would be New EAS. It is EAS without the wind speed. This velocity is still close to the IAS in airplanes exempting wind speed, but is very accurate due to its relative independence on atmospheric parameters. Let us call it new equivalent airspeed or NEAS.

We know the altitude z can be calculated by,

$Z = (RT/gM).\log_e(p_o/ p)$

$p_o/p=e^{(z/cT)}$

P and T are the pressure and temperature at the altitude of the airplane and Po &To are ground level conditions.

Where c is a constant R/gM = 29.285714

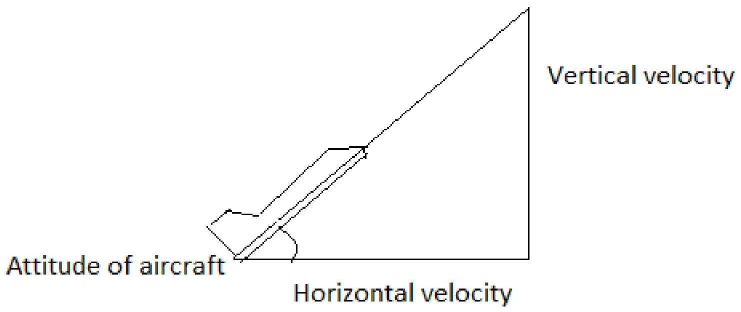
$NGS/NEAS = \sqrt{(\rho_o/\rho)} = \sqrt{p_o T/ p T_o}$

Then,

$NEAS = NGS \sqrt{(T_o/T\ e^{(z/cT)})}$

NEAS is the replacement to IAS in aircraft according to the requirement.

Calculation of attitude of an aircraft (minor addition):



The attitude of an aircraft can be calculated using both the velocity components. Application of inverse tan on Vv / Vh gives us the attitude of the aircraft

$\phi = \boldsymbol{tan^{-1}}\ (Vv/Vh)$

Experimental Results:

Most of the flight data of modern aircraft, simulations had to be used to validate the proposed theory. The values below are taken in different flights with different headings and altitudes at one instance of the flight in a computer simulation.

Coordinates in DEG

Lat1-16.92027778 Lon1-79.97361111 Lat2-16.92305556 Lon2-79.96722222 (5s)

Parameters	Values (Given\Calculated)
TAT	271
AL	4572
TAS	148.16
IAS	128
NGS	149.51
NEAS	115.6

The velocity given by the current system is GS 148.16 and new system 149.51.
Indicated airspeed 128, alternative method gives 115.6
Coordinates in RAD
Lat1-0.942023 Lon1-0.146594 Lat2- 0.942029 Lon2- 0.146570 (1s)

Parameters	Values (Given\Calculated)
TAT	250
AL	5258.88
TAS	103.91
IAS	80.84
NGS	97.977
NEAS	73.45

The velocity given by the current system is TAS 103.91 and new system 97.97. Indicated airspeed 80.84, alternative method gives 73.45

Wind speed = 80.84 – 73.45 = 7.4 m/s opposite to the flight direction.

Coordinates in RAD
Lat1-0.942053 Lon1- 0.146441 Lat2- 0.942056 Lon2- 0.146414 (1s)

Parameters	Values (Given\Calculated)
TAT	249.15
AL	5222.68
TAS	106.728
IAS	83.54
NGS	103.13
NEAS	77.54

The velocity given by the current system is TAS 106.72 and new system 103.13. Indicated airspeed 83.54, alternative method gives 77.54

Wind speed = 83.54 – 77.54 = 6m/s opposite to the flight direction.

Coordinates in DEG
Lat1-17.37194444 Lon1-79.28333333 Lat2-17.37138889 Lon2-79.29166667 (1s)

Parameters	Values (Given\Calculated)
TAT	266
AL	5486
TAS	165.137
IAS	128.097
NGS	177.609
NEAS	129.99

The velocity given by the current system is GS 165.13 and new system 177.609. Indicated airspeed 128.097, alternative method gives 129.99.

Wind speed = 128.097 – 129.99 = 1.02m/s in the flight direction.

Advantages:

1. The velocity calculated using this system is more accurate when compared to the current system and with no additional equipment or hardware cost involved.

2. It can be used for a close estimation of indicated airspeed and true airspeed in a situation of uncertain winds or bad weather conditions.

3. This can be used for ATh control in autopilot during uncertain winds and storm, avoiding the continuous thrust change caused due to fluctuating IAS value in bad weather conditions due to the pitot tube errors.

4. The difference between IAS and NEAS gives a much accurate Wind speed magnitude and direction with no additional measuring equipment on board.

Conclusion:

The GPS based system for calculating aircraft's speed and attitude provides a new velocity called New equivalent airspeed in an aircraft and also improves the accuracy of the existing ground speed in flying objects or objects moving at an altitude and is a substitute to the pitot static system.

It also is a GPS and software driven system which makes it relatively independent of mechanical devices and failures and requires no additional equipment on board. Not to mention the added advantage of minimum dependency on the ever-changing atmospheric conditions. This velocity can be used as a replacement for IAS in times of highly turbulent flow, storms or other uncertain atmospheric conditions to know the aircraft velocity. This will mainly help autopilots because the IAS of the aircraft changes quickly and shows a lot of error, and the autopilot tends to maintain the requested speed during these fluctuations spooling the throttle continuously to maintain the speed when in reality there wasn't any change in the speed of the aircraft and is only the pitot driven error due to winds. To avoid this the autopilot could use a stable version of the IAS which is NEAS of the aircraft and still be in the required speed.

Being directly calculated from GS of the aircraft, NEAS can be used for navigation at low altitudes due to the fact that the velocity includes the delay and drifts caused due to uncertain winds.