Localization and tracking of aircraft with ground based 3D sound probes

T.G.H. Basten[1], H.E. de Bree[2,3], E.H.G. Tijs[2]

[1]TNO Science and Industry
P.O. Box 155, 2600 AD Delft, The Netherlands
e-mail: tom.basten@tno.nl

[2]Microflown Technologies
P.O. Box 300, 6900 AH Zevenaar, The Netherlands
e-mail: debree@microflown.com, tijs@microflown.com

[3]HAN University
Department of Vehicle Acoustics
Ruitenberglaan 26, 6826 CC Arnhem, The Netherlands
e-mail: HE.deBree@han.nl

Key words: Acoustics, sound probes, sound source localization

Abstract: In this paper a new method is described for localizing and tracking low flying aircraft, based on compact and broadband three-dimensional sound probes. Recently, such sound probes became available based upon three orthogonally placed acoustic particle velocity sensors (Microflowns) and a single sound pressure sensor. With at least two of these sound probes, placed at a certain distance from each other, sound sources such as airplanes can be localized and tracked along its trajectory. The method is based on a triangularization technique using the particle velocity or sound intensity vectors. As an acoustic far field sound source localization technique, this approach has already been applied in wind tunnels. However, this method can also be used to localize the geometric position of a low flying aircraft along its trajectory.
Simultaneously, both the perceived noise level and acoustic signature of the flying object can be determined. Thus, this method can be expected to be used for both civil and defense purposes, for instance around heliports or borderlines. The method will be clearly described and test results of both lab scale and first true outdoor applications will be presented.

INTRODUCTION

Both for civil and military purposes information regarding the location and path of low flying aircraft and the corresponding sound radiation is often very important. Various acoustic measurement methods are developed for this purpose, that are all based on traditional sound pressure microphones [1-5]. Some of them have serious restrictions, such as the assumption that the aircraft flies on a straight line at constant speed and altitude [1-2]. Another method for determining the angle and distance (also called passive ranging) is done by using a microphone configuration which determines the wave front curvature. With at least three microphones and a correlation technique to determine the time delay between the sensor signals, the curvature in a single direction can be determined. From the effective speed of sound and the microphone configuration the distance between source and array and the angle between the source and the microphone array can be determined. This approach becomes very inaccurate when the distance between source and sensors is much larger than the array dimensions. For sources far away the wave fronts are approximately planar. In those cases with a single array only the angle of incidence can be determined and the source position can be found by triangularisation using the angles of multiple arrays. To do this in three dimensions with sufficient accuracy large arrays are needed, which are

unpractical. An alternative method is based on a four microphone method, where the distance from the probes is determined by measuring the angular shift which only shows up for high speeds of the aircraft [5]. It is clear that the microphone based methods have serious limitations and rely on assumptions which are often not valid.

In this paper a new method is described for localizing and tracking aircraft, enabled by the use of acoustic particle velocity sensors used in a very compact and broadband three-dimensional sound probes, see Figure 1. With these probes the three dimensional sound intensity vector can be measured.
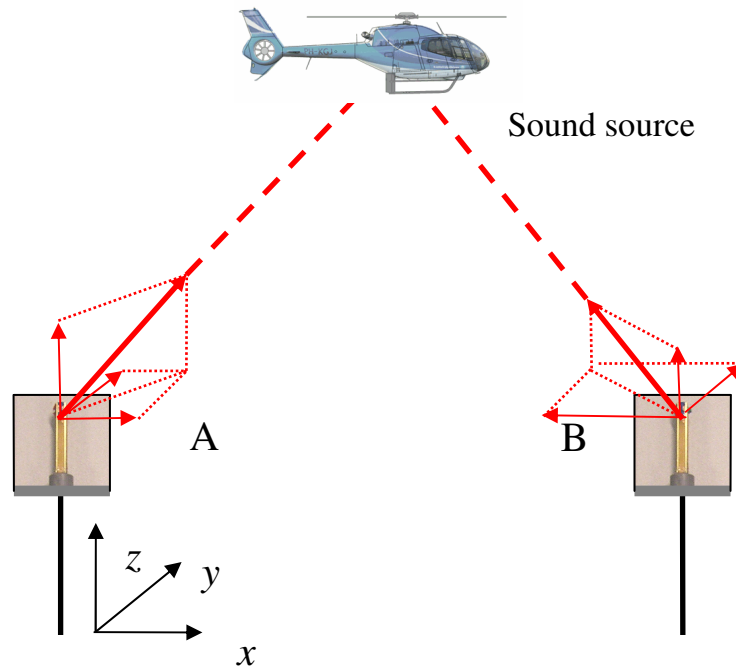

Figure 1. Two 3D probes to track the sound source location

This vector is used to determine the direction of the sound source. With only one probe, the phase information between sound pressure and particle velocity can be used to give an indication of the distance of the sound source. A more robust way is to use two or more of such probes to determine the location of the source by using a triangulation technique. The first results of the latter method are presented in this paper.

1. THE 3D SOUND PROBE

The method relies on the simultaneous measurement of sound pressure and acoustic particle velocity. In contrast to the acoustic pressure, the particle velocity is a vector quantity. So to reconstruct the total acoustic particle velocity vector, the particle velocity has to be measured in three directions. A commercial particle velocity sensor, called the Microflown, has recently become available [6]. Each particle velocity sensor is sensitive in only one direction, so three orthogonally placed particle velocity sensors have to be used. In combination with a pressure microphone, the sound field in a single point is fully characterized and also the acoustic intensity vector, which is the product of pressure and particle velocity, can be determined [7]. This intensity vector indicates the acoustic energy flow. For a single monopole source, the acoustic energy flows from the source

towards the sensor in a straight line. When the direction of the energy flow is known, the source can be found in the opposite direction. With a compact probe as given in Figure 2, the full three dimensional sound intensity vector can be determined within the full audible frequency range 20 Hz up to 20 kHz.

Figure 2. Microflown 3D sound probe. Three particle velocity elements (red, blue and green) are combined with a 1/10" pressure microphone

2. THE LOCALIZATION METHOD

2.1 Sound intensity

The intensity in a certain direction is the product of sound pressure (p) and the particle velocity component in that direction (u). The time averaged intensity in a single direction is given by Equation 1.

$$I = \frac{1}{T}\int_T p(t)u(t)dt \tag{1}$$

The sound intensity vector in three dimensions is composed of the acoustic intensities in three orthogonal directions (x,y,z):

$$\vec{I} = I_x\vec{e}_x + I_y\vec{e}_y + I_z\vec{e}_z \tag{2}$$

The vector indicates the acoustic energy flow from the source. The sound source can be found in the opposite direction of the sound intensity vector. So with one probe the direction is known, but not the distance to the source. For sources nearby, the phase relation between particle velocity and sound pressure can be used to given an indication of the distance. When the distance becomes larger, the phase between pressure and velocity becomes zero. Therefore another localization method is used based on triangularization with at least two probes.

2.2 Triangularisation using two probes

Two ground based sound probes, A and B are used, positioned at a certain distance from each other. When the two sound intensity vectors are known, the source position can be determined, using triangularization.

The measured sound intensity vectors at positions A and B are given by:

$$\vec{I}_A = I_{A,x}\vec{e}_x + I_{A,y}\vec{e}_y + I_{A,z}\vec{e}_z$$
$$\vec{I}_B = I_{B,x}\vec{e}_x + I_{B,y}\vec{e}_y + I_{B,z}\vec{e}_z \tag{3}$$

The normalized vectors pointing in the opposite direction, so from the probe to the source, are given by:

$$\vec{n}_A = -\frac{\vec{I}_A}{\left|\vec{I}_A\right|} \quad \text{and} \quad \vec{n}_B = -\frac{\vec{I}_B}{\left|\vec{I}_B\right|}, \tag{4}$$

where |.| indicates the length of the vector. Using these normalized vectors and the known positions of the two probes, two lines can be constructed connecting the probes and the sound source:

$$\vec{r}_A = \vec{d}_A + \lambda\vec{n}_A \quad \text{and} \quad \vec{r}_B = \vec{d}_B + \mu\vec{n}_B \tag{5}$$

Where $\vec{d}_A$ en $\vec{d}_B$ are the position vectors of the probes:

$$\vec{d}_A = d_{A,x}\vec{e}_x + d_{A,y}\vec{e}_y + d_{A,z}\vec{e}_z$$
$$\vec{d}_B = d_{B,x}\vec{e}_x + d_{B,y}\vec{e}_y + d_{B,z}\vec{e}_z \tag{6}$$

In theory the source should be on both lines and the source should be found at the position where both lines cross. However, in practice the vectors do generally not cross. Due to measuring and aligning errors, in general the two vectors are skew. Skew lines are lines or vectors which are not parallel and do not meet, see Figure 3. We assume the source to be on the position where the distance between the lines has a minimum. We thus seek the minimum distance between these lines.
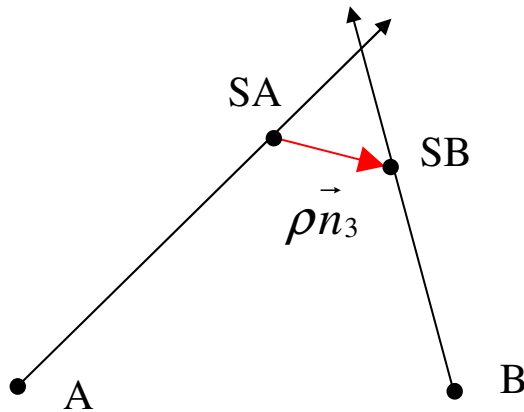

Figure 3. Two skew lines and its transversal (in red)

The shortest line between both lines is perpendicular to both lines. This line is called the transversal. The length of the transversal is:

$$\rho = (\vec{d}_B - \vec{d}_A) \cdot \frac{\vec{n}_A \times \vec{n}_B}{\left|\vec{n}_A \times \vec{n}_B\right|} \tag{7}$$

The transversal vector between the two lines is given by $\rho\vec{n}_3$. The points SA and SB are the points where the transversal crosses both lines, see Figure 3. The locations of the points are found by:

$$\vec{d}_{SA} = \vec{d}_A + \lambda_{SA}\vec{n}_A$$
$$\vec{d}_{SB} = \vec{d}_B + \mu_{SB}\vec{n}_B \tag{8}$$

Looking to Figure 3, it is easy to see that the following relation has to be valid:

$$\vec{d}_A + \lambda_{SA}\vec{n}_A + \rho\vec{n}_3 = \vec{d}_B + \mu_{SB}\vec{n}_B \tag{9}$$

Or in matrix form:

$$\{d_A\} + \lambda_{SA}\{n_A\} + \rho\{n_3\} = \{d_B\} + \mu_{SB}\{n_B\} \tag{10}$$

When the values for λ_A and μ_B are known, the positions of SA and SB can be calculated. The source S is assumed to be in the middle of SA and SB.

The values for λ_A and μ_B can be found by solving the following matrix equation:

$$\begin{bmatrix} \lambda_{SA} \\ \mu_{SB} \end{bmatrix} = \left[\{n_A\} \quad -\{n_B\}\right]^{-1}\{\{d_B\} - \{d_A\} - \rho\{n_3\}\} \tag{11}$$

The matrix which is inverted is not square, so instead of the inverse, the pseudo inverse has to be used. It is easy to show that the method can be extended with more probes, making the method more robust.

2.3 Limitations

Some limitations of the localization method are given here.

Meteo
The presented method assumes a straight line between the source and the probes. Meteo effects, such as wind and temperature variations in the air between source and probe, cause the propagation paths not to be straight. The meteo effects are especially important for small angles of incidence (grazing sound), because the air layer close to the ground has the largest variations in atmospheric conditions. Normally with increasing height the wind speed increases and the temperature decreases. This effect has not been accounted for in this stage of research. Also the other techniques found in the literature [1-5] rely on constant atmospheric conditions resulting in straight propagation paths.

Ground reflections
Special attention has to be paid to ground reflections. Due to the reflection a mirror source will be present and the total intensity vector will be a sum of the direct and reflected sound field. To

eliminate the ground reflections a sound absorbing surface under the two probes can be used. Another option is to use the directional properties of the particle velocity sensors. This will be investigated in the near future.

Singular positions
When the sound source is on the line between probes A and B, the two vectors indicating the source are on the same line and the source position cannot be reconstructed in the presented way. This problem can be solved by using extra sound probes.

Multiple sources
When multiple sources at various positions are present the total intensity vector will be composed from all contributions and will generally not indicate towards a single source. However sound intensity is increased with the square of the amplitude so in general the vector is dominated by the loudest source. Also the spectral contribution of the various sources can be used to discriminate between multiple sources.

Speed of aircraft
The speed of the aircraft is not taken into account. It is assumed that during fly over the position is quasi-static during small time intervals.

3. EXPERIMENTS

Experiments are performed to test the method. First the setup and calibration is described. Then three different experiments are described with increasing difficulty.

3.1 Experimental setup

The experimental setup is based on two three dimensional sound probes. The eight sensor signals (six particle velocity and two pressure signals) are recorded by using a regular sound card (Hercules 16/12) which is connected to a laptop by a firewire connection. The setup is powered by batteries making it completely suited for outdoor use.

3.2 Calibration

First, the sensors are calibrated. The piston on a sphere calibration method is used for calibration of the sensors [8]. This method is based on a loudspeaker built in a sphere, see Figure 4. The acoustic impedance at a given distance in front of the spherical source is known from theory, which is the basis of this velocity calibration technique for higher frequencies (f>100 Hz). The pressure element is calibrated for the full bandwidth (20 Hz up to 20 kHz). To calibrate the velocity elements for the lower frequencies the reference pressure microphone is put in the sphere. The pressure inside the sphere is proportional to the velocity of the loudspeaker membrane and the particle velocity at the probe position. This method works from 20 Hz up to 200 Hz. This way each sensor element of the 3D probe can be calibrated in the full acoustic bandwidth (20 Hz up to 20 kHz) with two measurements.
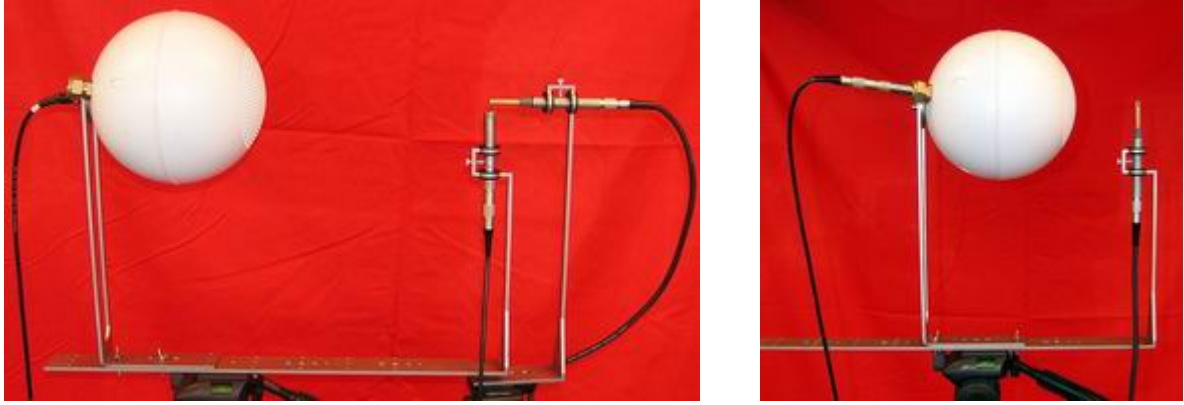
Figure 4. Piston on a sphere calibration of a 3D probe

3.3 Experiments in an anechoic room

Initially the measurement setup was tested in the anechoic room of TNO Science and Industry. The laboratory conditions are ideal because there are no reflections and there are no disturbances, such as wind. Two 3D probes are positioned 3.0 meter from each other, 1.5 meter from the ground, see Figure 5.
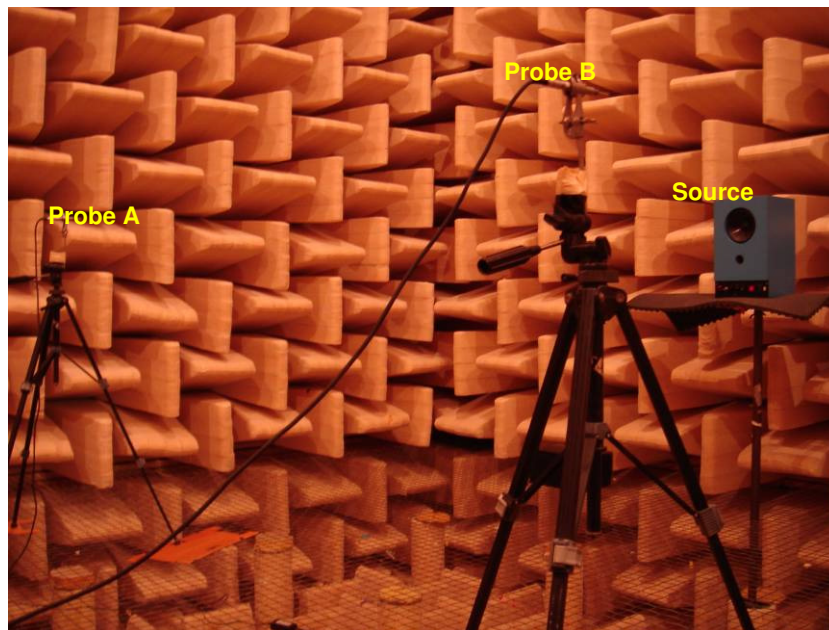

Figure 5. Measurement setup in the anechoic room

Only measurements are performed with a stationary source (a loudspeaker emitting white noise) which is placed successively at different positions. The position of the source is reconstructed using the measured sound intensity around 400 Hz. The results for two positions are given in Figure 6. The reconstructed position in both cases is within 0.5 m of the real position.
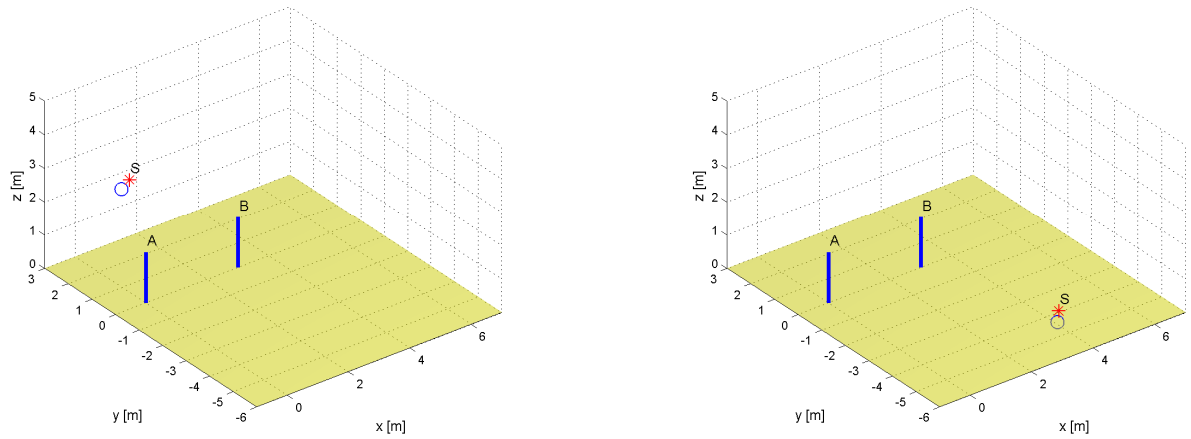
Figure 6. Results for two source positions S. The blue circle indicates the real source position. The red asterisk is the measured position. The lines A and B indicate the acoustic probes

3.4 Outdoor experiment

The second step is to localize and track a sound source in open air, see Figure 7. The probes are placed 3.0 meter from each other, 1.5 meter from the ground. Measurements are performed for a small stationary moving source, consisting of a loudspeaker moved by hand. The sound source is relative close by the probes because of limited loudspeaker signal level. These measurements were performed with wind shield, but without reflection cancelling and damping foam under the sensors. Because of the source positioning close to sensors, the influence of acoustic ground reflections is small.

Figure 7. Outdoor measurement using windshield protection

Some results of the moving source are given in Figure 8. A moving averaging procedure is applied which diminishes the influence of wind and other disturbing effects. The measured trajectories are close to the real trajectories of the source.
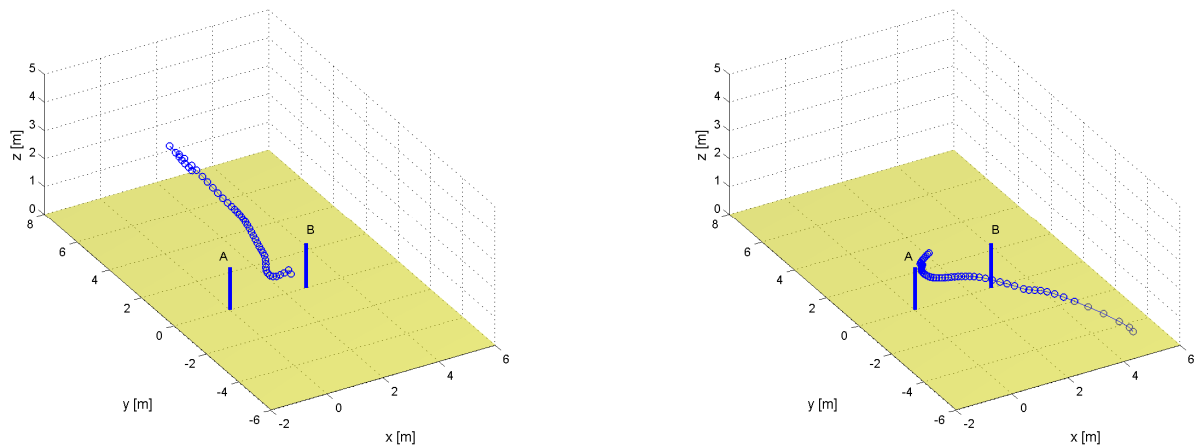
Figure 8. Measured trajectories of a moving source

3.5 Helicopter experiment

The third step is the localization and tracking of a helicopter during flight, see Figure 9. The probe distance is increased to 25.0 meter and the probes are placed 1.2 meter from the ground (grassland). Measurements are performed during landing and take off of a commercial helicopter (Eurocopter EC 120). The 20.5 Hz component, which is the blade-passage frequency of the main rotor, running at 410 rpm is used for detection.

Figure 9. Helicopter experiment

The vector components of $\{n_A\}$ and $\{n_B\}$ of the normalized vectors pointing from respectively probes A and B towards the helicopter during a landing procedure of 60 seconds are given in Figure 10. The blue line indicates the component at each time interval of 0.1 s. The green line is a moving average result which smoothes the random vector variations.
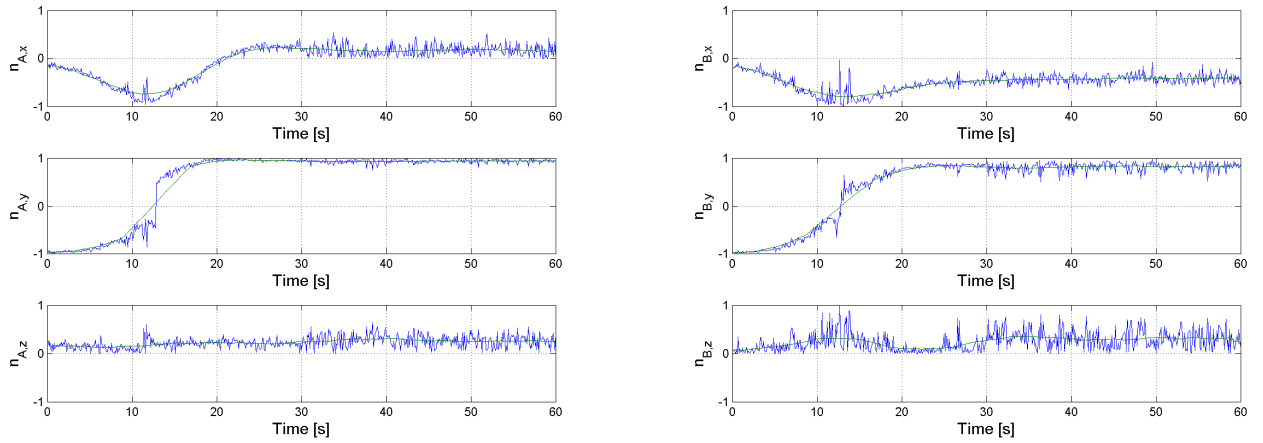
Figure 10. Vector components (x,y,z) of the two probes as a function of time

Some results for the reconstructed trajectory during landing are given in Figure 11. Also the moving averaging procedure is applied to the found location as a function of time during landing. The trajectories are close to the real trajectories of the source, but major improvements can still be made. Difficulties occur for example due to alignment of the probes, wind effects during fly over, reflections and sensor overload. But in essence the feasibility of the method is demonstrated and shows to have much potential.
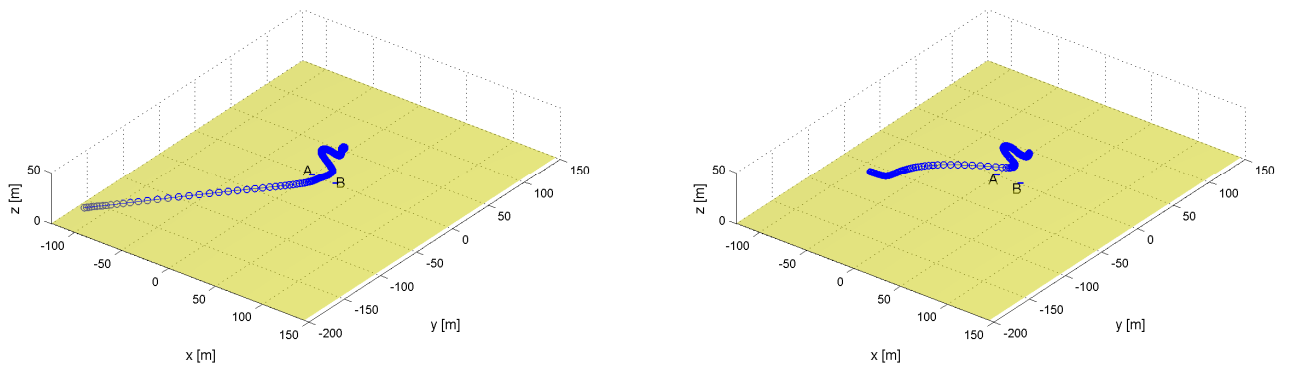

Figure 11. Trajectories of the helicopter during landing

4. DISCUSSION

The first results are quite promising, but significant improvements can still be made. In the first place the alignment between the two probes is very important and has to be improved. With a laser the adjustment can be made more accurately. Another idea is to calibrate the vector acoustically. A sound source is placed on a known position and the vector is adjusted so that it points exactly in that direction.

Also the positioning of the three sensors on a single probe is very important. The method assumes that the sensors are perpendicular to each other. This is not exactly the case, due to slight

inaccuracies during assembly. This problem can be avoided if the sensors can be integrated on one single monolithic chip. Currently such a probe is under investigation [9].

Besides, the sensor mounting has to be improved. Because of the wind the microphone stands and the wind cap grid itself moved. A more rigid construction is necessary.

The influence of reflections can be reduced considerably at higher frequencies by placing damping material under the probes. Also a reduction method for ground reflections using the directional behavior of the particle velocity sensor is under investigation.

When more than two probes are used, the method will be more robust and accurate. Also the existence of singular positions will be eliminated. Another design parameter which can be optimized is the distance between the probes. Issues like sensor sensitivity, signal strength, background noise are also points of research.

5. CONCLUSION

In this paper the feasibility of a new method for sound source localization and source tracking is demonstrated based on compact probes measuring the sound field in three directions. The feasibility of this method for localizing and tracking aircraft is demonstrated. The first results were quite promising in this early stage of research.

An important benefit of the new method is the omnidirectional source localization with only a few small three dimensional probes. Simultaneously, both the perceived noise level and acoustic signature of the flying object can be determined.

6. ACKNOWLEDGEMENTS

REFERENCES

[1] Brian G. Ferguson, "A ground-based narrow band passive acoustic technique for estimating the altitude and speed of a propeller driven aircraft", Journal of the Acoustical Society of America, 92(3), pp 1403-1407, 1992.
[2] Brian G. Ferguson and Kam W. Lo, "Turboprop and rotary-wing aircraft flight parameter estimation using both narrow-band and broadband passive acoustic signal-processing methods", Journal of the Acoustical Society of America, 108(4), pp 1763-1771, 2000.
[3] Brian G. Ferguson, "Variability in the passive ranging of acoustic sources in air by using a wavefront curvature technique", Journal of the Acoustical Society of America, 108(4), pp 1535-1544, 2000.
[4] F.M. Dommermuth, "A simple procedure for tracking fast maneuvering aircraft using spatially distributed acoustic sensors", Journal of the Acoustical Society of America, 82(4), pp 1418-1424, 1987.
[5] N. Roosnek, "Passive ranging with four microphones in a spatial configuration", Internoise 2001, The Hague, The Netherlands, 2001.

[6] H.E. de Bree, P. Leussink, T. Korthorst, H. Jansen, T. Lammerink and M. Elwenspoek, "The Microflown: a novel device measuring acoustical flows", Sensors and Actuators A-Physical, 54, pp 552-557, 1996.

[7] F. Jacobsen and H.E. de Bree, "A comparison of two different sound intensity measurement principles", Journal of the Acoustical Society of America, 118(3), pp 1510-1517, 2005.

[8] F. Jacobsen and V. Jaud, "A note on the calibration of pressure-velocity sound intensity probes", Journal of the Acoustical Society of America, 120(2), pp 830-837, 2006.

[9] Yntema, D.R., Wiegerink, R.J., van Honschoten, J.W., Elwenspoek, M., Fully integrated three dimensional sound intensity sensor. MEMS 2007, Kobe, Japan, 2007