DATA PROCESSING KIT FOR
MULTI-HOLE PROBE RAKES

For use with MD24HP-series 'Hydra' rakes

WARNING

Read this document before using the software.

This system is not certified for use on aircraft.

Contents

1 INTRODUCTION 1
2 THIRD-PARTY SOFTWARE AND DRIVERS 2
3 CALIBRATION ALGORITHM 4
4 CALIBRATION DATA RESTRUCTURING 5
5 MEASUREMENT DATA CONVERSION 10
6 TECHNICAL SUPPORT 13
Appendix: Reference coordinate systems 14

Version Control

Version	Date	Summary of changes	Software release
1.0	12-2025	New document	1.0

1 INTRODUCTION

Principle of operation

This is a generalized data reduction algorithm which converts the pressures obtained from rakes of multihole probes with arbitrary configurations and channel numbers into three components of velocity. This software utility was developed specifically for use with the MD214HP-series Hydra rakes, but may be used with any multi-hole probe rake system providing that the data files are formatted and stored appropriately.

System description

Software application and development kit for multihole probe rakes.

System components

Calibration data resampler	Utility for converting unstructured calibration data files into the structured data formats required for the data reduction process
Data converter	Utility for converting measured pressures from rakes of arbitrary configurations into three components of velocity (with uncertainty estimates)
Development kit	Software development kit for National Instruments LabVIEW environment
Sample data	Examples of data file formats needed

2 THIRD-PARTY SOFTWARE AND DRIVERS

There are two external drivers which must be downloaded and installed on the computer in order for the PC to be able to interface with the rake system, in addition to the specific system driver for your rake.

- National Instruments LabView Run Time Engine (LVRTE)
- National Instruments VISA Run-Time Engine (NIVISA)

These drivers are freely available for download from National Instruments. Ensure that the 64-bit version of the NI LabVIEW Run Time Engine is selected (note this is not the default option), and restart the computer following each installation. Correct download settings for each driver are shown in figures 6 and 7 below.

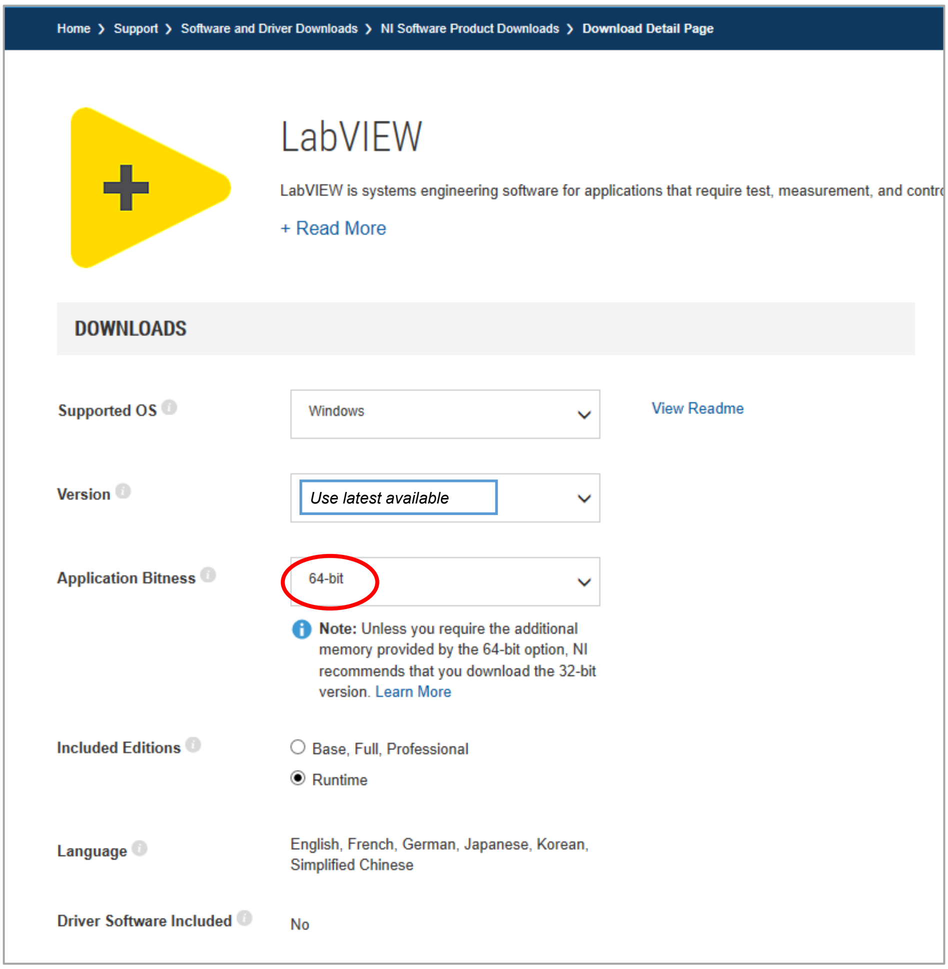

Figure 1: Download settings for NI LabVIEW Runtime Engine

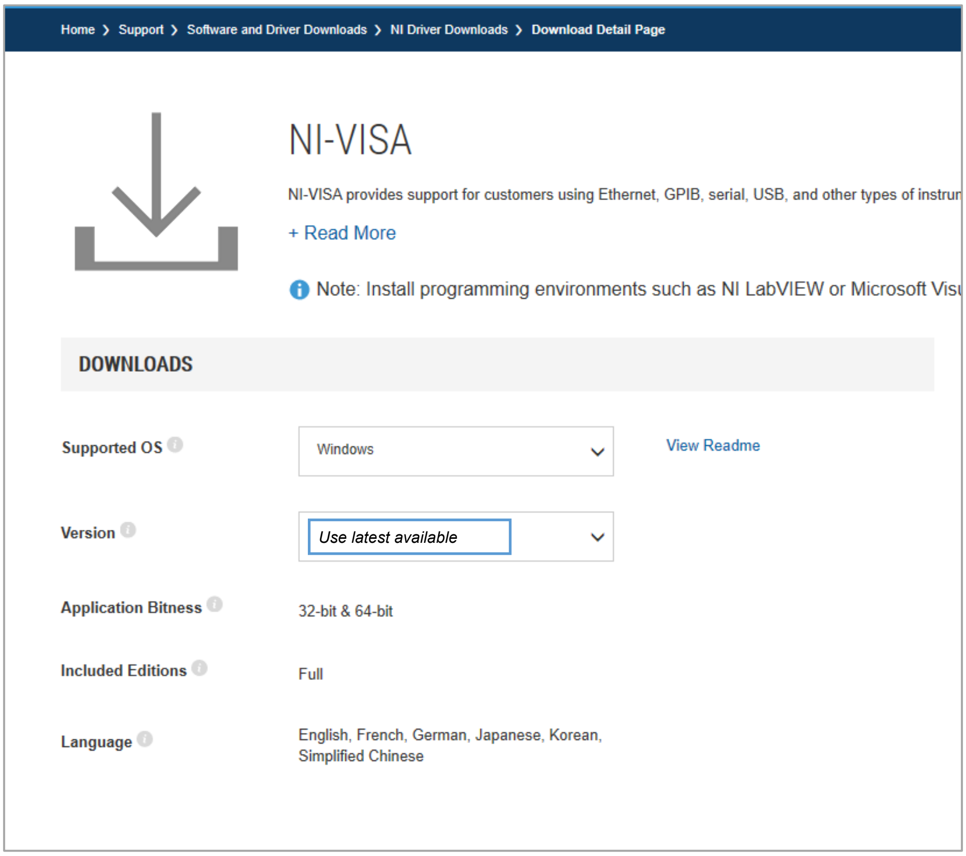

Figure 2: Download settings for NI VISA Runtime Engine

All of the software packages are compatible with 64-bit NI LabVIEW 2022-Q3 or later. For other versions, please contact your Surrey Sensors Ltd. sales representative.

3 CALIBRATION ALGORITHM

The calibration algorithm used is the generalized, sectorless technique based on that of Shaw-Ward *et al*[1], but updated to accommodate unsteady flows.

The pressure at each hole i on a particular probe sting (having any number of holes *n*) is reduced to a nondimensional coefficient C_i as

$$C_i = \frac{P_i - P_{min}}{P_{max} - P_{min}}$$

where P_i is the differential pressure recorded at hole i = 0,1, 2, ..., *n*-1; P_{max} and P_{min} are the maximum and minimum differential pressures recorded over all holes on a particular probe sting, respectively, and *n* is the number of holes. These coefficients are reasonably independent of velocity magnitude, but calibration should still be carried out near the expected operating speeds or at the centre of the expected range. During calibration, empirical functions $C_i(\alpha, \beta)$ are obtained (where α and β are the pitch and yaw angles) as well as a stagnation differential pressure coefficient C_0.

During measurement, then, P_i is converted into C_i and an interpolation process is used to return the closest matching flow angles. With the matching flow angles then known, C_0 can be interpolated from the calibration data at those angles, returning the local stagnation pressure; the velocity magnitude can then be obtained from the stagnation pressure.

This generalized data reduction process is independent of the number of holes in the probe head and their arrangement (although three independent measures of pressure are fundamentally required in order to resolve three components of velocity). Typically, the uncertainty in a particular measurement will decrease with increasing hole numbers. Figure 3 shows the ranges of relative mean-square error ε as a function of number of holes *k* in a hemispherical-tip probe; error bars show variability in uncertainty with hole arrangement.

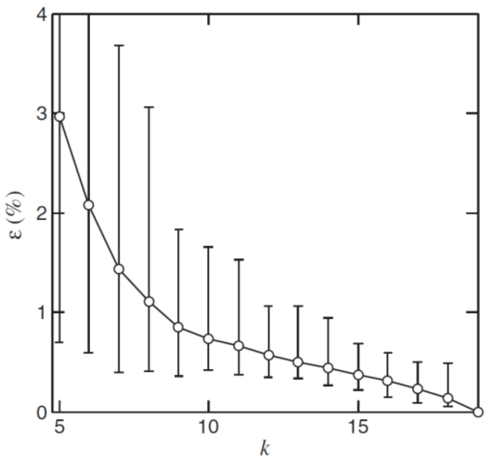

Figure 3: MSE Uncertainty bounds for arbitrarily positioned holes in a hemispherical-tip probe (from Shaw-Ward et al.[1])

[1] Shaw-Ward, S., Titchmarsh, A. and Birch, D. M. (2015) "Calibration and use of *n*-hole velocity probes." AIAA J. 53(2), 336-346.

4 CALIBRATION DATA RESTRUCTURING

Calibration files will normally be supplied as an unstructured list of data points; to be used in the data reduction process, these must first be converted into structured grids.

Calibration data file
The unstructured calibration data file must be in ASCII tab-delimited format with two header rows. An example of this (from a 24-element rake) is included in the sample data directory as [`\raw calibration files\angle calibration file.txt`]. The file may have any name and any extension, but the extension must be included any time the file name is used.

For a calibration file having *n* pressure measurements, the columns of the calibration data file must be organized as follows (with units as indicated):

α (deg)	β (deg)	P_0 (Pa)	P_1 (Pa)	...	P_{n-1} (Pa)	U_{REF} (m/s)	ρ (kg/m^3)	P_{ATM} (mBar)	T_{ATM} (°C)	RH (%)	a_x (g)	a_y (g)	a_z (g)

The variables are defined as follows:

- α and β: these are the prescribed angles of pitch and yaw (respectively) for each calibration point.
- P_0, P_1, ..., P_{n-1}: these are the list of pressures P_i for each calibration point, where i = 0, 1, ..., n-1 and *n* is the number of pressure sensors. Note that P_0 here is the pressure at hole index [0], and ***not*** the stagnation pressure.
- U_{REF}: This is the free-stream speed at which the probe was calibrated. At every calibration point, then, $(u^2 + v^2 + w^2)^{1/2} = U_{REF}$ by definition.
- ρ: This is the estimated density of the fluid during calibration. Normally, this is approximated from the ideal gas law as $\rho = P_{ATM}/(\mathcal{R}T_{ATM})$, where $\mathcal{R}$ is the specific gas constant of the fluid ($\mathcal{R}$ ~ 287.05 J/kgK for dry air).
- P_{ATM} and T_{ATM} : These are the ambient static pressure and temperature (respectively) during calibration. Note that P_{ATM} only is expressed in mBar (= Pa/100) here, for legacy reasons.
- *RH*: This is the relative humidity of the air at the time of calibration. The assumption here is that the calibration was carried out in air; if the humidity is unknown, enter zeros in this column.
- a_x, a_y and a_z: The MD24HP-series rakes return the acceleration vector at each calibration point, for alignment purposes. These are not used as part of the calibration process; if not available, they may be populated with zeros.

Rake configuration file
The rake is assumed to consist of a main body or mast, with multiple independent stings such that each sting is a multi-hole probe having three or more holes. The rake configuration file identifies which pressure channels are associated with which sting so that these can be treated independently; otherwise all of the pressure measurements would be lumped together by the generalized calibration process such that the entire rake becomes an *n*-hole probe with a measurement volume spanning the entire length of the rake.

The rake configuration file must appear in the same directory as the calibration data file. The filename can be user-specified, but it must begin with an underscore character in order to be identified as the configuration file. In the sample data provided (from a rake of three seven-hole probes having three additional unused pressure channels), the configuration file has the name [`_sting metadata.txt`].

The configuration file must have two columns, with two header rows. The data must be organized as follows:

Channel index	Sting ID

The [`Channel index`] is the channel number *i* corresponding to the column of pressure data P_i in the unstructured calibration data file and the measurement data files. These can be in any order, but must include all numbers from 0 through *n*-1 inclusive. The indices do not need to have the same configuration from sting to sting, and stings do not have to be of the same configuration or relative orientation - as long as this is consistent between the calibration and measurement files. The [`Sting ID`] is an arbitrary index assigned to each independent probe on the rake, starting with 0. When particular channels are unused or not connected, the [`Sting ID`] of those channels is set to the value [`-1`]

IMPORTANT: The rake configuration file (having the default file name [`_sting metadata.txt`], and which must have a leading underscore in the file name) must be in the same directory as the directional calibration data file or the software will terminate in error.

Generating calibration data files

To facilitate (and accelerate) the interpolation process, the calibration data files used by the testing executable need to be in the form of structured grids in (α, β). These are saved as independent files in user-readable ASCII format, for verification purposes. Appropriately-formatted calibration files may be generated from a single unstructured table of data points using the calibration file generation tool, CALIBRATION_RAKE_RESAMPLER.EXE.

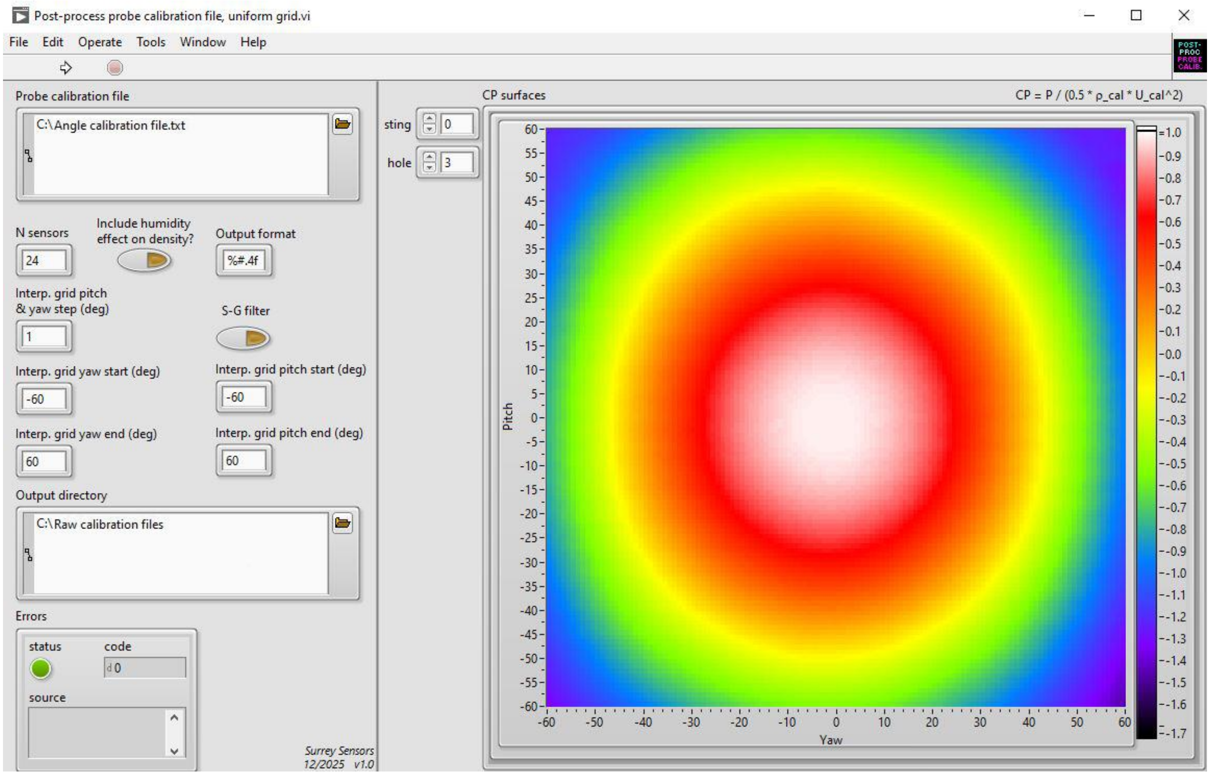

Figure 4: Calibration data resampler user interface

Operating instructions:

Step 1: Identify the unstructured (raw) calibration data file as described above. Once the file is identified, click on the folder icon in the [CALIBRATION RAW DATA INPUT FILE] field and navigate to the file location; select the file and click [OK]. The rake configuration file [`_sting metadata.txt`] must be located in the same directory.

Step 2: Locate directory for output files. The output files must all be in the same directory. Once the directory is identified, click on the folder icon in the [OUTPUT DIRECTORY] field and navigate to the directory location. Click on [CURRENT FOLDER] to select the active directory currently open in the window.

Step 3: Enter desired parameters for resampling. This software will interpolate your data over a regular grid, as required for the data conversion process. The user can tailor how this is done. The editable parameters are as follows:

N Sensors: Enter here the total number of pressure measurements from the rake. This should correspond to the number *n* of pressure channels appearing in the data files.

Include humidity effect on density?: When this button is enabled, the density estimates of the fluid will be adjusted to account for the relative humidity in the calibration data. If relative humidity data is not available, this should be left disabled.

Output format: This allows the user to modify the precision of the output data. Normally, this should be left to four decimal places, or [%#.4f], for calibration files.

Interp grid pitch & yaw step (deg): This allows the user to specify the grid spacing over which the data will be resampled. It is normally recommended that this be set to the raw data grid spacing (or smallest spacing, if a nonuniform measurement grid was used). Data will be resampled to the specified grid spacing using a piecewise nonlinear interpolation.

S-G filter: This option is available to minimize the influence of noise in the data fields, and reduce the uncertainty if the individual data points were not well converged. When enabled, a Savitzky-Golay[2] filter is used to smooth the fields.

Interp. grid. pitch start (deg): Minimum pitch angle at which calibration data will be required. This should normally be the minimum angle at which calibration data were obtained, although the option is available to use only a subset of the available raw data.

Interp. grid. yaw start (deg): Minimum yaw angle at which calibration data will be required. This should normally be the minimum angle at which calibration data were obtained, although the option is available to use only a subset of the available raw data.

Interp. grid. pitch end (deg): Maximum pitch angle at which calibration data will be required. This should normally be the maximum angle at which calibration data were obtained, although the option is available to use only a subset of the available raw data.

Interp. grid. yaw end (deg): Maximum yaw angle at which calibration data will be required. This should normally be the maximum angle at which calibration data were obtained, although the option is available to use only a subset of the available raw data.

Step 4: Run the executable. This is done by clicking on the arrow icon under the menu bar.

If the executable ran without error, a green indicator will appear under [STATUS] in the [FILE ERROR] field.

Once processing is complete, the executable will also display a contour plot of pressure coefficient as a function of α and β. The results from individual holes and stings can be selected using the [STING] and [HOLE] selectors. The sting number will correspond to the index appearing in the rake metadata file, while the hole number is assigned sequentially. Note that the hole number does not correspond to the channel number.

Output files

The rake calibration data resampler will generate a number of output data files which will later be used for data reduction.

(a) Unstructured probe calibration data files

For convenience, the resampler will produce unstructured calibration data files for each of the probes in the rake, having the file name [*_sting_?.txt], where [*] indicates the name of the original unstructured rake calibration data file, and [?] is the probe ID index assigned

---

2 Schafer, R. W. (2011) "What is a Savitzky-Golay Filter?" IEEE Sig. Proc. 28(4).

in the second column of the configuration file [_sting metadata.txt.txt]. These probe calibration files contain the same data as the rake calibration data file, just sorted per probe. These files are provided for convenience only, and are not used.

(b) Sting data output directories

Within the identified data output directory, sub-directories named [Sting_?] will be created, where [?] is again the Sting ID index. These directory names must not be changed.

Each of these output directories will be populated with structured data files for each of the parameters used as part of the data reduction process.

(c) Calibration files

Within each calibration directory, the structured calibration files will appear as follows:

Parameter	Filename
Pitch angles	Pitch_cal.txt
Yaw angles	yaw_cal.txt
Velocity	U_cal.txt
Density	rho_cal.txt
Pressures	P*_cal.txt

(d) Configuration file

For convenience, a copy of the rake configuration file [_*.txt] will also be added to the output directory.

IMPORTANT: The structured calibration data file names must not be changed, or the data reduction software will not be able to locate them. The output data directory must contain no other directories than the [Sting_?] directories generated by the resampler.

5 MEASUREMENT DATA CONVERSION

Data file format
Measurement data files will generally be in the form of time-histories from each of the sensors, measured simultaneously. The data conversion software requires a data file having two header rows, and columns as follows:

t (s)	P_0 (Pa)	P_1 (Pa)	...	P_{n-1} (Pa)	T_{ATM} (°C)	P_{ATM} (Pa)	T_B (°C)	RH (%)	a_x (g)	a_y (g)	a_z (g)	ω_x (°/s)	ω_y (°/s)	ω_z (°/s)

The variables are defined as follows:

- t: this is the time at which each measurement was collected, normally measured from the start of acquisition.
- P_0, P_1, ..., P_{n-1}: these are the list of pressures P_i for each calibration point, where i = 0, 1, ..., n-1, and n is the number of channels. Note that P_0 here is the pressure at hole index [0], and ***not*** the stagnation pressure.
- T_{ATM} and P_{ATM} : These are the ambient static pressure and temperature during measurement, which are required for data reduction.
- T_B : This is a measure of the system's internal temperature and is used for health monitoring. This is not used for data reduction; if the values are unavailable, enter zeros in this column.
- RH: This is the relative humidity of the air at the time of measurement. The assumption here is that the measurements were carried out in air; if the humidity is unknown or if the fluid was other than air, enter zeros in this column.
- a_x, a_y and a_z: The MD24HP-series rakes return the acceleration vector at each measurement point. These are not used as part of the data reduction process; if not available, these columns may be populated with zeros.
- ω_x, ω_y and ω_z: The MD24HP-series rakes also return the angular velocity vector at each measurement point. These are not used as part of the data reduction process; if not available, these columns may likewise be populated with zeros.

Converting measurement data
The data reduction software [RAKE_DATA_CONVERTER.EXE] will read in a measurement time-history file and convert the pressures into three components of velocity for each of the probes on the rake. The corresponding time-histories of the three components of velocity at each of the stings will be saved separately, together with useful indications of data quality.

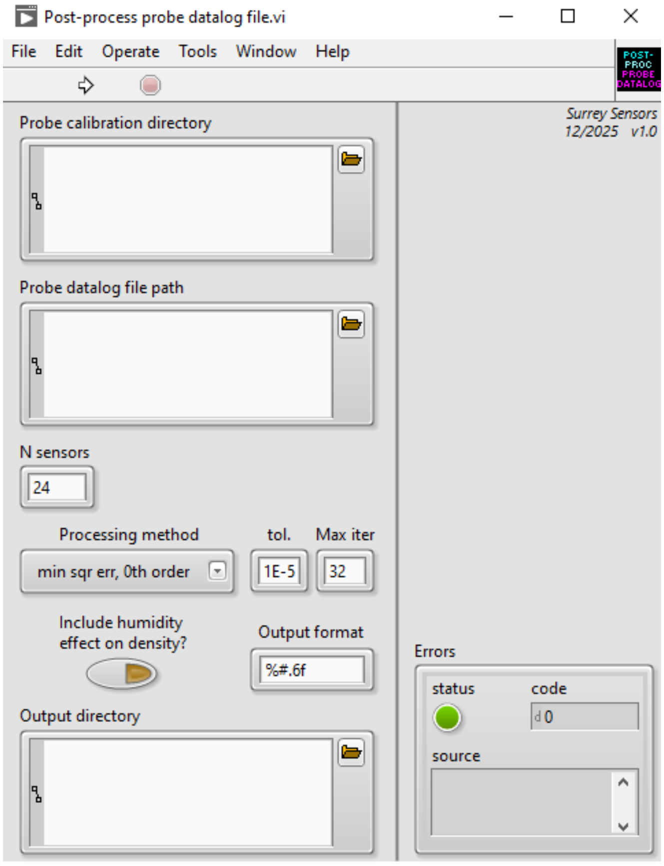

Figure 5: Data converter user interface

Operating instructions:

Step 1: Click on the folder icon in the [PROBE CALIBRATION DIRECTORY] field and navigate to the directory containing the [`STING_?`] sub-directories. When these directories are visible in the navigation window, click the [SELECT FOLDER] button to select the currently active directory. The rake configuration file [`_*.txt`] must also be in this directory.

Step 2: Locate the measurement data file. Once the file is identified, click on the folder icon in the [PROBE DATALOG FILE PATH] field and navigate to the file. Select the file and click [OK].

Step 3: Select or create a directory for output files. The output files will all be saved in the same directory. Click on the folder icon in the [OUTPUT DIRECTORY] field and navigate to the directory location. Click on [CURRENT FOLDER] to select the active directory currently open in the window.

Step 4: Enter desired parameters for data conversion. The editable parameters are as follows:

N Sensors: Enter here the total number of pressure measurements from the rake. This should correspond to the number *n* of pressure channels appearing in the calibration data files. Because the indexing starts at [0], the highest channel index will be *n*-1.

Processing method: This instructs the software which method to use when interpolating from the calibration data grids; different techniques will yield slightly different results, and the quality of the output from each technique may vary depending on the measurements collected. Note that [0TH ORDER] does not interpolate and instead returns the closest point from the calibration.

Tol.: This is the convergence threshold for the interpolation process. A value of 10^{-5} (entered as [1E-5]) is recommended.

Max iter.: This allows the user to specify the maximum number of iterations in the interpolation process, to avoid hang-ups on oscillating solutions. A value of [32] is recommended.

Include humidity effect on density?: When this button is enabled, the density estimates of the fluid will be adjusted to account for the relative humidity in the measurement data. If relative humidity data is not available or not relevant, this should be left disabled.

Output format: This allows the user to modify the precision of the output data. Normally, this should be left to six decimal places, or [`%#.6f`].

Step 5: Run the executable. This is done by clicking on the arrow icon under the menu bar.

If the executable ran without error, a green indicator will appear under [STATUS] in the [FILE ERROR] field. The user may then inspect the outputs.

Output files
Within the output directory, an output data file will be created for each of the stings. The files will have the names [`Processed results, Sting_?.txt`], where [?] represents the sting index as it appears in the rake configuration file.

a sub-directory will be generated for each of the probes, having names of the form [`Sting_?`], where[?] is the sting ID index. In each of these directories will be an output file for that particular sting, having the name [`Combined results file.txt`]. Additional data output files will also be generated for each of the output parameters.

Within the combined output file, there will be one header line containing column labels, followed by data arranged in columns as follows:

t (s)	U (m/s)	V (m/s)	W (m/s)	U_{MAG} (m/s)	α (deg)	β (deg)	ρ (kg/m^3)	ΔC_p	n_{IT}	*Conv-erged*

The variables are defined as follows:

- t: this is the time of the data point, reproduced from the original (raw) data file.
- U, V, W: these are the three orthogonal velocity components obtained from the data reduction process. The directions x, y and z are defined by the coordinate system used during calibration.

- U_{MAG}: this is the magnitude of the output velocity, obtained from the velocity components as $U_{MAG} = (U^2 + V^2 + W^2)^{1/2}$.
- α and β: these are the angles of pitch and yaw (respectively) of the output velocity, obtained from the velocity components.
- ρ: this is the density estimate used for data reduction at this point.
- ΔC_p: this is the estimated maximum interpolation error in pressure coefficient at this point.
- n_{IT}: this is the number of iterations required to achieve convergence at this point. Note that this is not relevant if "zeroth order" interpolation was selected under [PROCESSING METHOD].
- *Converged?*: This is a check-bit for convergence. The value will be [0] if the interpolator was unable to converge to a solution at this point, so that the data returned will be invalid. Note that this is not relevant if "zeroth order" interpolation was selected under [PROCESSING METHOD].

6 TECHNICAL SUPPORT

Full technical support is available for the implementation of this software with Surrey Sensors Ltd. products.

If you experience any difficulty in installation or use, or if you need additional support in the operation of the system, please contact your Surrey Sensors Ltd. account manager or technical representative.

Appendix: Reference coordinate systems

The spherical coordinate system commonly used in physics (ISO 80000-2:2019 convention) is adopted here and used throughout. By convention, the pitch angle α increases with rotation toward the *z*-axis, and the yaw angle β is positive rotating anti-clockwise about the *z*-axis (see figure 9). Here, *u*, *v* and *w* are the velocity components along *x*, *y* and *z*, respectively.

In some early data reduction algorithms, the cone angle θ and roll angle φ were used. These are not relevant here.

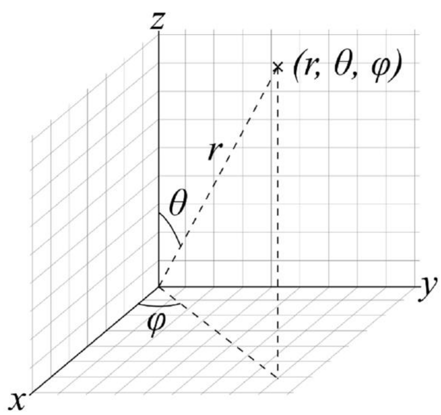

Figure 6: Coordinate conventions

In all cases, by convention, the pitch angle α and yaw angle β are defined as

$$\alpha = 90° - \theta$$
$$\beta = \varphi$$

Probe-based coordinate system:

This convention is intended for use on a moving platform, such as an aircraft or vehicle.

$$u = |U| \cos(\beta) \cos(\alpha)$$
$$v = |U| \sin(\beta) \cos(\alpha)$$
$$w = |U| \sin(\alpha)$$

Wind tunnel-based coordinate system:

This convention is intended for use in stationary-probe wind tunnel applications with a right-handed coordinate system with the probe pointing in the upstream *x* direction, such that the z-axis is vertical (environmental flow convention).

$$u = |U| \cos(\beta) \cos(\alpha)$$
$$v = -|U| \sin(\beta) \cos(\alpha)$$
$$w = |U| \sin(\alpha)$$

Rotated wind tunnel-based coordinate system:

This convention is intended for use in stationary-probe wind tunnel applications with a right-handed coordinate system with the probe pointing in the upstream *x* direction, such that the y-axis is vertical (aerospace flow convention).

$$u = |U| \cos(\beta) \cos(\alpha)$$
$$v = |U| \sin(\alpha)$$
$$w = |U| \sin(\beta) \cos(\alpha)$$