Measurement Guidelines for VOC Analysis by PTR-MS

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Summary: These measurement guidelines provide information that enables proper operation of PTR-MS in the field and address quality assurance parameters needed to produce high-quality data sets that meet the ACTRIS standard.

These guidelines contain the following topics:

1. General introduction

The final Standard Operation Protocol (SOP) for VOC measurements (Actris deliverable WP4/D4.9 v.2014/09/30) reports guidelines for online measurements using Gas Chromatography (GC) but only preliminary recommendations were given for Proton Transfer Reaction-Mass Spectrometry (PTR-MS). The present document is a supplement to the SOP mentioned above and as such replaces section 5.2 in the ACTRIS deliverable WP4/D4.9 v.2014/09/30.

While compound identification by online gas chromatography remains the standard technique for many purposes, PTR-MS is complementary for the following reasons:

- Minimize potential losses or the spurious formation of VOCs during the sampling stage since ambient air is directly analyzed (within seconds after sampling) without any pre-concentration step,
- Reduce artifacts due to sample conditioning since PTR-MS does not require sample pretreatment to remove O_3 or water before analysis,
- Provide fast time resolution (as high as 10 Hz) together with high sensitivity and low limits of detection,
- Untargeted quantitative analysis is possible.

The aim of these guidelines is to provide information that enables proper operation of many types of PTR-MS for trace gas measurements in ambient air and procedures to test quality assurance (QA). The report also provides the information needed to produce high-quality datasets that meet the ACTRIS standard.

These guidelines cover:

- Commercialized instruments equipped with conventional drift tubes (DC electrical field and operating pressure of a few mbar) and Time of Flight Mass Spectrometers (ToFMS). Only remarks are provided for PTR-MS equipped with Quadrupole Mass Spectrometers (QMS) that are not commercialized anymore,
- Proton transfer reactions using hydronium ions (H_3O^+), other ionization methods using NO^+, O_2^+, NH_4^+ and other reagent ions are not covered,
- Proper operations in the field: sampling, zeroing, calibrating, extracting and reporting data. Remarks are also provided for the use of PTR-MS on atmospheric simulation chambers.

2. Principle of the PTR-MS technique

Only a brief description of the measurement principle is given below and the reader is referred to recently published reviews for more details.[1–4] Ambient air is sampled continuously into a reactor held at a pressure of a few mbar where trace gases can be ionized by proton transfer reaction using the hydronium ion, H_3O^+, and its ionic water-clusters, $H_3O^+(H_2O)_n$ n=1, 2, … The pressure is kept low enough in order that only a single collision is possible between the primary reagent ion and a trace gas that leads to the protonation of the latter. In the reactor, reagent ions and ionized trace gases are transported through the application of an electrical drift field, which limits water clustering, and then extracted into a mass spectrometer for detection and quantification.

Instruments are composed of the following units:

- ***Ion source:*** generates a high flux of H_3O^+ primary reagent ions, alternative reagent ions (NO^+, O_2^+, etc.) are minimized,
- ***Reactor:*** typically set up as a drift tube reactor where trace gases are mainly ionized via collisions with H_3O^+ ions. The energetic conditions in the reactor should be well defined and quasi-homogeneous (spatial and temporal) in order to provide well-constrained reaction kinetics,
- ***Ion transfer unit:*** this component is made of regular electrostatic lenses, or more advanced ion optics to increase the efficiency of ion transfer to the mass spectrometer. An ideal ion transfer unit will conserve the collision energetics of the reactor,
- ***Mass spectrometer:*** first models of PTR-MS were incorporating a Quadrupole Mass Spectrometer (QMS) but new models are equipped with Time of Flight Mass Spectrometers (ToFMS). ToFMS exhibit several advantages compared to QMS such as better ion transmissions at high m/z, the rapid acquisition of the whole mass spectra, and the separation of some isobaric compounds (i.e. species with the same nominal mass but different elemental composition),
- **Inlet**: this component is a flow or pressure-controlled system that will carry ambient trace gases from the sampling point to the reactor, ideally without any interaction between the targeted analytes and walls from tubing or other parts. Temperature-regulated capillary inlets are usually used to reduce wall effects.

Required properties for PTR-MS instruments (discussed in sections 3 and 4):

- High ion purity. The sum of all impurities (O_2^+, NO^+, NH_4^+, etc.) should be lower than 3% of [$H_3O^+ + H_3O^+(H_2O)$],
- Negligible chemical processing of the sample gas by radicals/photons from the ion source,
- The reaction kinetics in the reactor generally comply with the simple kinetics scheme published by Hansel et al. (1995)[4] and described below. Limitations and exceptions must be well constrained and explained (e.g. back reaction for formaldehyde). This includes the requirement that H_3O^+ must constitute at least 80% of the reagent ions, $H_3O^+ + H_3O^+(H_2O)_n$, under normal operating conditions,
- Collision energetics in the reactor must be nearly homogeneous and well constrained. In addition, the electrical field has to be tuned to minimize fragmentation of protonated trace gases (e.g. <30% for isoprene when $E/N \leq 130$ Td),

- Collision energetics in the transfer region must be well constrained. Ion intensities for species produced from endothermic reactions (N_2H^+ or CO_2H^+) in the transfer region should be minimized,
- Parameters of the mass spectrometer (mass resolution, mass accuracy, transmission, peak shape) must be well constrained,
- Raw data (mass spectra) must be recorded and accessible to the user.

In order to be detected by PTR-MS, an analyte has to exhibit a larger proton affinity than water. Table 1 reports VOCs that have been selectively monitored by PTR-ToFMS with a mass resolution (m/Δm) larger than 4000 in different types of environments (remote, forested, urbanized, biomass burning plumes) and that have been found to be almost exempt of interferences from both isomeric compounds and the fragmentation of other protonated species. Some potential interferences are indicated in the table caption for specific environments. For PTR-ToFMS instruments exhibiting a lower resolution and PTR-QMS instruments some interferences may arise from isobaric species and the reader is referred to Yuan et al. (2017)[1] for additional details.

Table 1: Proton affinity of selected species

Species	Formula	m/z	Proton Affinity (kJ mol^{-1})
Water	H_2O		691
Methanol	CH_3OH	33.033	754
Acetonitrile	C_2H_3N	42.034	776
Acetaldehyde[a]	C_2H_4O	45.033	769
Acetone[b]	C_3H_6O	59.049	812
Isoprene[c]	C_5H_8	69.070	831
Methyl Ethyl Ketone[d]	C_4H_8O	73.065	826
Benzene[e]	C_6H_6	79.054	750
Toluene[f]	C_7H_8	93.070	784
C8-aromatics	C_8H_{10}	107.086	≈ 790
C9-aromatics	C_9H_{12}	121.101	≈ 790
Monoterpenes	$C_{10}H_{16}$	81.070 + 137.132	≈ 780

Yuan et al. (2017)[1] & Coggon et al. (2024)[2]*: [a] potential interference from ethanol ionization by O_2^+ if formed in the ion source, [b] small contribution from propanal (<10%), [c] potential interferences from cycloalkanes and higher-carbon aldehydes (urban), 2-methyl-3-buten-2-ol (forest), methylbutanals (forest), 1-penten-3-ol (forest), [d] Methyl ter-butyl ether and butanals (urban, biomass burning), [e]* fragmentation from ethylbenzene and benzaldehyde (urban),*[f] fragmentation from higher aromatics (urban) and monoterpenes (forest).*

Many other VOCs exhibiting proton affinities larger than water can also be detected by PTR-MS but the selective and quantitative nature of their measurements have to be carefully evaluated. A non-exhaustive list of additional VOCs detected by PTR-MS is reported in Annex 1 and larger databases are available online (PTR Library[6,a], GLOVOCS[7,b]). For instance, species such as formaldehyde, which exhibit a proton affinity (713 kJ mol^{-1}) that is only slightly higher than that of water, are difficult to quantify accurately due to a significant deprotonation rate that is dependent on humidity, which in turn induce a humidity-dependent PTR-MS response. In addition, formaldehyde measurements at m/z 31.018 could also be biased in some environments by the detection of fragments from protonated methyl hydroperoxide, methanol and ethanol. Alcohols are another class of compounds that is difficult to quantify in ambient air by PTR-MS due to protonated analytes undergoing dehydration (loss of H_2O). This requires a good understanding of fragmentation patterns for each targeted alcohol. The latter also

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[a] https://sites.google.com/view/de-gouw-lab/instruments/ptr-library
[b] http://glovocs.creaf.cat/

precludes the quantification of alkenes since dehydrated ions from protonated alcohols are detected at the same exact mass than alkenes.

For drift reactors that comply with the requirement of quasi-homogeneous energetic conditions (spatial and temporal), the volume mixing ratio of a protonated analyte, VMR, is derived from the measured analyte signal, C_{AH^+}, and the knowledge of parameters associated to the reactor design (d), operating conditions (N, E, K_0, $C_{H_3O^+}$, $C_{H_3O^+(H_2O)}$) and the analyte under consideration (k), as shown in Equation 1.

$$VMR = \left. \frac{C_{AH^+} \times IF_{AH^+} \times FF_{AH^+}}{C_{H_3O^+}} \middle/ \left(\frac{T_{AH^+}}{T_{H_3O^+}} \times \frac{d \times k}{\mathrm{K}_0 \times N_0} \times \frac{N^2}{E} \right) \right. \qquad \text{Eq. 1}$$

In Eq. 1, VMR is the volume mixing ratio, C_X (counts) the total signal detected over the measurement duration for species X (X=AH^+, H_3O^+), IF_{RH^+} an isotopic correction factor (see below), FF_{RH^+} a correction factor accounting for the potential fragmentation of AH^+ (see section 3b), d (cm) the length of the reactor, E (V/cm) the voltage applied to the reactor per unit of length, T_X the transmission for species X, k (cm^3 molecule^{-1} s^{-1}) the proton transfer reaction rate constant for the detected VOC, N (molecule cm^{-3}) the density of molecules in the reactor, N_0 (molecule cm^{-3}) and K_0 (cm^2 V^{-1} S^{-1}) the density of molecules and the H_3O^+ ion mobility in air at 1 atm and 0°C, respectively. It is worth noting that C_X signals are often reported in units of counts s^{-1} in PTR-MS software while these signals are expressed in units of counts for the total duration of a measurement in the following. The latter can be calculated from the signal expressed in counts s^{-1} multiplied by the measurement duration in s.

The inclusion of an isotopic correction factor (IF_{AH^+}) in Eq. 1 is necessary since C_{AH^+} is only quantified from the detection of the most abundant isotopes (all carbon atoms being ^{12}C, oxygen atoms being ^{16}O, nitrogen atoms being ^{14}N and hydrogen atoms being ^{1}H). C_{AH^+} has to be corrected on the basis of the known natural abundance of stable isotopes as illustrated in the example below.

Example: *A measurement of isoprene derived from the ion signal recorded at m/z 69.070 indicates a mixing ratio of 2.5 ppbv.*

What is the mixing ratio expected for the sum of all ambient stable isotopes?

The detection of isoprene at m/z 69.070 is from its most abundant isotope ($^{12}C_5{}^1H_8$), whose natural abundance is 94.544%. In order to account for the presence of other stable isotopes (^{13}C, ^{2}H), the measured VMR at m/z 69.070 has to be multiplied by a factor of 1.057 (calculated as 1/0.94544).

Measurements of analytes containing heteroatoms such as chlorine and bromine, which exhibit two isotopes with significant abundances (^{35}Cl: 75.8% & ^{37}Cl: 24.2%, ^{79}BR: 50.6% & ^{81}Br: 49.4%), will also require a correction of the measured signal depending on which isotope is detected at the selected m/z. If all isotopes can be selectively quantified at different m/z, it is preferred to sum all measured isotopes together instead of applying a correction to calculate the VMR (EX: dichlorobenzene is detected at m/z 113.016 and 115.013 due to the presence of ^{35}Cl and ^{37}Cl).

When the protonated analyte fragments significantly in the drift reactor, the VMR can be retrieved accurately if both the parent and fragment(s) ions are selectively monitored. VMR retrieved at the parent and fragment(s) m/z are summed to calculate the ambient VMR of the analyte as described in the example below. However, if the fragment(s) cannot be selectively monitored, the VMR measured for the parent ion has to be corrected for fragmentation (IF_{AH^+} in Eq. 1). This correction factor can be assessed during calibration as discussed in section 3.b.

> ***Example:*** *Monoterpenes ($C_{10}H_{16}$) detected at 137.132 m/z significantly fragments at 81.070 m/z. Equation 1 is used to quantify VMR measured at these two m/z, the measured VMR are corrected for isotopic abundances as described above, and the sum is used as the ambient monoterpene VMR. Here potential fragments at other m/z are neglected.*

It is worth noting that Eq. 1 only accounts for proton transfer reactions involving H_3O^+ ions. Proton transfer from reactions of analytes with $H_3O^+(H_2O)$, which occurs when the analyte's proton affinity is higher than the water dimer's proton affinity (808 kJ mol^{-1}), is not accounted for. This is not an issue when H_3O^+ constitute at least 80% of the reagent ions [$H_3O^+ + H_3O^+(H_2O)_n$] as recommended in these guidelines. However, a deviation from these operating conditions could lead to a water dependent response of PTRMS instruments for some compounds, which should be investigated as discussed in section 3b.

For the H_3O^+ ion signal needed in Eq. 1 ($C_{H_3O^+}$), its large abundance in the drift reactor precludes detection at the main isotope peak due to saturation of the detector. Instead, the signal recorded for a less abundant isotope is used and corrected by the known natural isotopic ratio as shown in Table 2. This table also provides m/z and isotopic ratios for other ions of interest in PTR-MS.

Table 2: Reagent ion quantification

Reagent ion	Main isotope m/z		Less abundant isotope m/z		Isotopic ratio
H_3O^+	$H_3{}^{16}O^+$	19.018	$H_3{}^{18}O^+$	21.022	487
$H_3O^+(H_2O)$	$H_3{}^{16}O^+(H_2{}^{16}O)$	37.029	$H_5{}^{17}O^{16}O^+$ $DH_4{}^{16}O_2{}^+$	38.033	645
			$H_3{}^{18}O^+(H_2{}^{16}O)$ $H_3{}^{16}O^+(H_2{}^{18}O)$	39.033*	242
$O_2{}^+$	${}^{16}O_2{}^+$	31.990	${}^{16}O^{18}O$	33.994	242
NO^+	${}^{14}N^{16}O^+$	29.998	${}^{14}N^{18}O^+$	32.002	487

** Quantification of $H_3O^+(H_2O)$ at m/z 39.033 may be prone to interferences from the detection of $C_3H_3{}^+$ in some environments*

Other parameters required to calculate VMR from measured signals ($C_{H_3O^+}$, C_{AH^+}) in Eq.1 are known from the instrument design and operating conditions (d, N, E, K_0) or tabulated in the literature (k), with the exception of the instrumental mass discrimination (T_{AH^+}, $T_{H_3O^+}$), which is referred to as "transmission" in the following. Since the transmission function is instrument dependent, calibrations are needed to quantify it over the m/z range of interest (including T_{AH^+}, $T_{H_3O^+}$). This method is referred to as 'kinetic approach' in section 3.b. Recommended reaction rate constants have been published by several authors (for instance Zhao et al.[8] and Cappellin et al.[9]) and are reported in the PTRLibrary database (tinyurl.com/PTRLibrary)[6]. For unknown compounds the usually recommended value is 3×10^{-15} m^3 s^{-1} since most proton transfer rate constants range from 2-4×10^{-15} m^3 s^{-1}.

A second method can also be used to derive VMR of ambient species from PTR-MS measurements when only a few targeted analytes have to be monitored. Here, the instrument's sensitivity is directly calibrated for the targeted species and a simplified form of Equation 1 (Eq. 2) is used to calculate ambient VMR from the measured signals and a normalized sensitivity, $S_N(AH^+)$. This approach is referred to as 'calibration approach' in section 3b.

$$VMR = {\frac{C_{AH^+}}{C_{H_3O^+}} \times 10^6} \Big/ {S_N(AH^+)} \qquad \text{Eq.2}$$

The factor 10^6 in Eq. 2 is introduced to normalize the measured C_{AH^+} signal to a reagent ion flux of 1 million cps (counts per second). The sensitivity $S_N(AH^+)$ is also normalized to 10^6 cps of H_3O^+ during the calibration procedure (section 3.b).

The main advantage of this method is its user friendliness. As seen when comparing Eqs. 1 and 2, the calibrated sensitivity includes the mass dependent transmission efficiency but also possible fragmentation, and automatically accounts for isotope peaks. However, this method does not provide a quantification of analytes that are not present in the calibration mixture in contrast to the kinetic approach that enables the quantification of untargeted VOCs.

3. Quality Assurance

a. Blank measurements

PTR-MS is not a zero-background measurement technique due to VOC sorption processes (adsorption/desorption) inside the sampling line and the drift tube, which requires frequent blank measurements to track background signals at all m/z of interest. The quality of the zero gas is essential as residual mole fraction on the order of tens of pmol/mol (pptv) can lead to negative offsets in ambient measurements when the blank signals (referred to as $C_{AH^+}^{blank}$ in the following) are subtracted from ambient signals (sections 3.b and 5).

VOC free air can be produced from ambient air using (i) a catalyst (Platinum Pt, Palladium Pd) held at a temperature of 350-400°C, (ii) a VOC scrubber containing a solid sorbent, or (iii) a cylinder of dry zero air (high purity, 5.0) with a humidification system containing high purity water. However, the catalyst is preferred to measure PTR-MS blank signals at the same humidity than ambient air since the desorption rate of surface-contaminants is water-dependent. When performing blanks, zero air is provided at the tip of the PTR-MS inlet (see Fig. 1, P15) at a flow rate larger than the PTR-MS sampling flow rate, with the excess air being vented at atmospheric pressure.

Commonly observed blank values for compounds reported in Table 1 are given in Table 3. These values are characteristic of Time of Flight Mass spectrometers (TofMS, m/Δm > 3000) where the peak of interest has been properly deconvolved from other adjacent peaks. Ranges of blank values are reported here since it depends on the inlet material, tightness of the drift-tube, the cleanness of the water and on the sampling history of an instrument. However, blank values significantly larger than the upper limit reported in this table should be investigated to ensure proper measurements.

Blank values have been observed to be strongly dependent on ambient humidity and the frequency of blank measurements should therefore depend on how fast humidity changes at the measurement site. Automated hourly determinations are usually sufficient, with at least two blank measurements per day to ensure that diurnal variations in instrumental blanks are well captured during operation in the field. It is important to note that a freshly installed instrument often has larger blank values than a long-time running one and it is recommended to perform more frequent blanks at the beginning of a campaign. When PTR-MS are used for laboratory experiments lasting at most one day, such as atmospheric simulation chamber experiments, a blank measurement performed at the beginning or end of the experiment is sufficient.

When zeroing the instrument, sufficient time should be allowed to allow gas-surface interactions to reach an equilibrium. The duration of the blank will depend on the inlet tubing and other internal materials inside the PTR-MS (temperature regulated PFA and surface treated stainless steel tubes result in quickest response times) and the chemical property of the compounds of interest. For example, acetonitrile will equilibrate quickly while acetic acid will result in a longer equilibration time. It is recommended to perform blank measurements over a duration that is long enough to reach stable signals by the end of the blank period, below that observed for ambient concentrations of targeted m/z. If not, the duration of blanks should be increased and the cause for long memory effects should be investigated. Only stable zero measurements will be used as blanks. Figure A2.1 (annex 2) illustrate it for the semi-volatile species of cis-pinonic acid for a traditional PTR-MS instrument with Peek inlet capillaries and an instrument optimized for fast equilibration responses (PFA and Sulfinert only, coating of the inner surface of the drift tube to avoid losses of low-volatility species). For the conventional instrument, cis-pinonic acid blank measurements will need to last several tens of minutes to achieve reliable blank values, while for the optimized PTR-MS, this period is reduced to 3-5 min.

Example: A PTR-MS instrument is deployed in the field for ambient measurements. Frequent blanks are performed using a permanently flushed zero air line (produced out of ambient air with a catalytic converter) by injecting zero air via a three-way valve at the PTR-MS inlet as shown in Fig.1 (P15). Blanks are done at different and varying times of a day (e.g. every 3.5 h) in order that periodic diurnal events will never be completely hidden by a blank measurement.

Table 3: Blank values for PTR-ToFMS

Species	Formula	m/z	Blank values (pptv)*
Methanol	CH_3OH	33.033	30-90
Acetonitrile	C_2H_3N	42.034	30-110
Acetaldehyde	C_2H_4O	45.033	40-270
Acetone	C_3H_6O	59.049	60-500
Isoprene	C_5H_8	69.070	20-70
Methyl Ethyl Ketone	C_4H_8O	73.065	10-70
Benzene	C_6H_6	79.054	20-80
Toluene	C_7H_8	93.070	20-140
C8-aromatics	C_8H_{10}	107.086	10-110
C9-aromatics	C_9H_{12}	121.101	5-200
Monoterpenes	$C_{10}H_{16}$	81.070 + 137.132	60-100 + 10-50

**Range of values observed on several PTR-ToFMS (m/Δm>3000). Reported values are for systems which have been running for at least several days. PTR-QMS may exhibit larger values due to the detection of isobaric species generated in the ion source and desorbing from the inlet material.*

b. Calibration

Two different calibration methods have been proposed to quantify PTR-MS signals, namely the ‘kinetic approach’ and the ‘calibration approach’. This section describes these two methods and provides information on how to check for VOC fragmentation.

For both approaches described below, zero air and a calibration gas are sequentially sampled through the PTR-MS inlet until a stable plateau is reached for each VOC signal. Both zero air and the calibration gas have to be generated at the same humidity.

Kinetic approach – This method relies on the well-defined conditions in the drift tube and known kinetics of proton transfer reactions as described in the principle section and discussed in details in Holzinger et al. (2019).[10] The volume mixing ratio of a VOC, including compounds for which no calibration standard is available, is retrieved from fundamental physical conditions in the drift tube (length, pressure, E/N, ion mobility, etc.) and compound specific parameters such as reaction rate constants as shown in Eq. 1. This procedure involves calibrating ion transmissions over the mass range of interest.

Calibrating the transmission requires the use of a standard mixture containing VOCs for which proton transfer rate constants are well known. For instance, the National Physical Laboratory (NPL, United Kingdom) provided a SI-traceable standard containing 20 compounds tailored to the requirements of PTR-MS (Annex 3).[11] A first prototype of this standard was used for the PICAB study.[10] The standard covers the mass range 33-672 Da with no overlap in protonated compounds, fragments and the water adducts thereof. This mixture contains VOC mixing ratios close to 1 ppmv and a dilution system is necessary to perform calibrations at mixing ratios of a few ppbv, which are high enough to quantify ion transmissions with a sufficient precision. To retrieve the transmission curve, it is recommended to only select compounds from the calibration standard that do not fragment in the drift tube, with the exception of fragmenting compounds such as alpha pinene or siloxanes (see NPL standard in Annex 3) whose fragmentation pattern (fragments' m/z and relative abundance) is well defined under the PTR-MS operating conditions. Transmission-corrected fragmentation patterns can be found elsewhere[11] for monoterpenes. For siloxanes, both the parent and fragment ions are detected at large m/z (m/z > 207 Da, Annex 3), i.e. in a region where ion transmission is close to 100%. This allows calculating fragmentation ratios from the measured signals without having to correct for ion transmission.

The use of a humidification system allowing to vary RH from 30-90% at ambient temperature is recommended for calibrations. In practice, the transmission is calibrated at the lowest humidity (e.g. 30% RH). Most PTR-MS instruments are provided with software allowing a retrieval of ion transmission from calibration data.

A transmission function derived from calibration should display a concave increasing trend that gradually levels off into a plateau, with all individual points smoothly connected (Fig. A4.1 – Annex 4). The presence of outliers (Fig. A4.2 – Annex 4) may indicate extrinsic factors, such as partial transmission of certain species from the calibration cylinder to the drift tube (e.g. pressure regulator delay) or high humidity, as well as intrinsic factors, including inhomogeneous E/N or too high pressure. If outliers are observed, the user should investigate the reason. These outliers should not be part of the final transmission function.

While the PTR-MS response for some VOCs can be sensitive to humidity due to additional ionization pathways involving ionic clusters, i.e. $H_3O^+(H_2O)$, only minor inaccuracies should be introduced if more than 80% of the reagent ions are H_3O^+. However, unwanted fragmentation and/or clustering in the ion transfer region (including MS ion guides and ion funnels) can also impact the distribution of reagent ions, so that the fraction $H_3O^+(H_2O)/ H_3O^+$ cannot be accurately inferred from the count rates at the respective m/z. Some tests should therefore be performed varying humidity over the 30-90% RH range to evaluate whether humidity-dependent responses are observed on the PTR-MS. During these tests VOC mixing ratios should be kept the same when humidity is varied, the PTRMS being used to monitor deviations in expected VMR (using ion transmission values retrieved from the calibration performed at the lowest humidity). If a significant humidity-dependent response is observed for some species, a humidity-dependent correction should be applied on the measured VMR or an additional source of error should be factored in the measurement uncertainty.

Fragmentation patterns of species of interest should be investigated during calibrations to determine whether the parent ion and fragments' VMR can be summed together (see principle section, feasible if both the parent ion and fragments are selectively detected) or whether a correction has to be applied on the parent ion VMR (FF_{AH^+} in Eq. 1) as described in the example below.

> ***Example:*** *The parent ion of isoprene is detected at m/z 69.070 and its fragment at m/z 41.039. However, due to the presence of interfering species in ambient air, the isoprene fragment cannot be reliably monitored and it is necessary to correct the VMR measured at m/z 69.070 for fragmentation as indicated in Eq. 1. A calibration performed using a standard mixture containing isoprene allows a reliable quantification of VMR (or transmission-corrected signals) at both 69.070 and 41.039 m/z. A correction factor can be computed as follows*
>
> $$FF_{AH^+} = \frac{VMR(69.070\ m/z) + VMR(41.039\ m/z)}{VMR(69.070\ m/z)}$$
>
> *It is important to note that correction factors for targeted VOCs are specific to the drift tube operating conditions (pressure, temperature, E/N) and have to be determined under field operating conditions.*

Calibration approach – This second approach has been introduced by de Gouw and Warneke[4] and relies on gas standard measurements from which compound specific normalized sensitivities are calculated by rearranging Eq. 2. This approach requires to use a calibration standard containing all the targeted compounds.

VOC Signals recorded when zero air or the calibration gas are sampled by the PTR-MS are referred to as $C_{AH^+}^{blank}$ and $C_{AH^+}^{cal}$, respectively, and are extracted from the mass spectra at m/z of targeted protonated VOCs (see section 5). Mean values of these signals, computed when plateaus are reached, are used to infer the net signal generated by each VOC ($C_{AH^+} = C_{AH^+}^{cal} - C_{AH^+}^{blank}$), which is then normalized to 10^6 cps of reagent ions. The net normalized signal of a VOC is divided by its VMR to calculate a normalized sensitivity $S_N(AH^+)$ expressed in normalized counts per second and per ppbv (ncps ppbv^{-1}).

For the calibration approach, corrections and rules have been developed[4] to properly account for humidity-dependent sensitivities as discussed above for the kinetic approach. Equation 3 is used instead of Equation 2.

$$VMR = \frac{\frac{C_{AH^+}}{C_{H_3O^+} + Xr \times C_{H_3O^+(H_2O)}} \times 10^6}{S_N(AH^+)} \qquad \text{Eq. 3}$$

Here, the net signal of a protonated VOC is normalized to a sum of reagent ions including both H_3O^+ and $H_3O^+(H_2O)$, where the latter is weighted by a multiplicative factor X_r. In practice, $S_N(AH^+)$ is derived from calibrations performed over a large range of relative humidity, typically 30-90%, and X_r is adjusted to remove any water dependence in $S_N(AH^+)$. The X_r parameter is therefore compound dependent and has to be determined for each VOC whose sensitivity exhibits a significant humidity dependence. Additionally, Xr may be instrument-dependent if the collision energetics in the transfer region differ from those in the drift tube (e.g., resulting in hard collisions). Therefore, Xr values should be determined for each specific instrument under its standard operating conditions. Examples of determinations of X_r and $S_N(AH^+)$ values are shown in Annex 5.

Calibration Frequency – Calibrations using either the "kinetic approach" or the "calibration approach" should be performed once a week (including the start and end of the campaign) when the campaign lasts less than two months and twice a month when long term measurements are conducted (> two months). If a significant drift in sensitivity is observed since the installation of the instrument (decrease of more than 20% at the highest m/z), re-optimization of the detector high voltage should be considered (Annex 6).

For laboratory experiments such as atmospheric simulation chambers, both the kinetic and calibration approaches can be used at the beginning and/or end of the experiment campaign. Nevertheless, another approach relying on repeated introductions of known amount of the compounds of interest into the atmospheric simulation chamber can also be used. It is however highly recommended to verify the generated concentrations using independent optical instrumentation such as FTIR. Uncertainties associated to these measurements will have to be factored in the calibration accuracy discussed in section 3c.

Check fragmentation ratios – Users should also take advantage of the calibration experiments discussed above to verify that transmission-corrected fragmentation patterns of fragmenting compounds present in the calibration gas are consistent with that expected from the PTR-MS operating conditions (E/N ratio). This verification is important to ensure that no extra fragmentation is taking place within the instrument due to potential technical issues or the use of improper operating conditions with extraction lenses/ion guides. Compounds suitable for verifying fragmentation ratios include isoprene and α-pinene, which should not fragment more than 30 and 60% at 130 Td, respectively. Instruments with transmission-corrected fragmentation larger than these values at 130 Td should be investigated to identify the underlying cause.

c. Figures of merit

This section describes how to compute mass resolution and accuracy, measurement precision and accuracy, as well as limit of detection (LOD). Both precision and LOD are primarily limited by counting statistics of product ions and follow a Poisson distribution.

Mass resolution and accuracy – A mass resolution larger than 3500 and a mass accuracy better than 2.5 ppm are sufficient to ensure proper deconvolution of isobaric peaks and proper assignment of elemental composition for $C_xH_yO_z^+$ ions up to m/z 445 when the peaks' signal-to-noise ratios are large enough.[13, 16]

The mass resolution for a peak detected at a targeted $(m/z)_{peak}$ can be calculated on the basis of eq. 4, where $\Delta(m/z)_{FWHM}$ is the peak's full width at half maximum.

$$R_{FWHM} = \frac{(m/z)_{peak}}{\Delta(m/z)_{FWHM}} \qquad \text{Eq. 4}$$

The mass accuracy at the targeted m/z can be estimated by computing the difference between the peak mass determined experimentally on the mass spectrum (after mass recalibration as described in section 5) and the exact mass calculated from the elemental composition of the ions detected at this m/z. In practice, commercial software provided with PTR-MS instruments allow checking changes in mass accuracy over times

Measurement precision - The volume mixing ratio of an analyte is derived from the subtraction between ambient ($C_{AH^+}^{ambient}$) and blank ($C_{AH^+}^{blank}$) signals measured during ambient and zero air sampling, respectively. This quantity is denoted C_{AH^+} ($C_{AH^+} = C_{AH^+}^{ambient} - C_{AH^+}^{blank}$) in Eqs. 1-3. The precision on C_{AH^+} is calculated for each targeted species from a quadratic propagation of errors associated to $C_{AH^+}^{ambient}$ and $C_{AH^+}^{blank}$, with 1σ errors calculated from the square root of the measured signals (Poisson statistic). The equation below assumes that $C_{AH^+}^{ambient}$ and $C_{AH^+}^{blank}$ have been acquired for the same duration.

$$\sigma_{precision} = \sqrt{C_{AH^+}^{ambient} + C_{AH^+}^{blank}} \qquad \text{Eq. 5}$$

Where $C_{AH^+}^{ambient}$ and $C_{AH^+}^{blank}$ are expressed in counts.

Note that Eq. 5 yields the precision in units of counts, which is usually not meaningful by itself. Division by the measured net signal (i.e. $C_{AH^+}^{ambient}$- $C_{AH^+}^{blank}$) as shown in Eq. 6 will yield a dimensionless fractional precision (i.e. the relative standard deviation, RSD) that also applies to the calculated mixing ratio. The absolute precision on the VMR is then calculated as RSD × VMR.

$$RSD(precision) = \frac{\sigma_{precision}}{C_{AH^+}^{ambient} - C_{AH^+}^{blank}} \qquad \text{Eq. 6}$$

It is important to note that this equation is only valid for computing the RSD when measurements are above the Limit of Quantification (LoQ), where LoQ = (10/3) × LoD, in order that the denominator of Eq. 6 remains positive. Measurements falling between the LoD and LoQ should be flagged accordingly.

Example: *Consider ambient air measurements at a time resolution of 0.5 seconds. Every full hour the background is measured for 10 minutes (also every 0.5 seconds). On average, the background signal is 10 counts per second (cps), but individual 0.5 s values typically range between 0-30 cps. An individual ambient measurement yields 120 cps for a certain ion.*

What is the signal and the precision of this individual measurement?

The ambient signal ($C_{AH^+}^{ambient}$) in the half second is 60 counts, and the signal attributed to the targeted ion is 55 counts (C_{AH^+}), because we expect 5 counts to be due to the background ($C_{AH^+}^{blank}$). Accordingly, the precision is 8.1 counts ($\sqrt{60+5}$), and the RSD is 0.15 (i.e. 8.1/55) or 15%.

What is the precision if 1-minute average values are computed?

Let us assume that during the minute of consideration an average ambient signal of 120 cps has been recorded. So, a total of 7200 counts have been registered over 1 minute, of which 600 are attributed to the background signal. So, the net signal for the targeted ion is 6600 counts (7500-600). The precision is 88 ($\sqrt{7200+600}$) counts, and the RSD is 1.3% (i.e. 88/6600).

Measurement Accuracy – The accuracy represents a systematic error estimated from calibrations and will depend on the approach used to calibrate the instrument:

(i) If the 'calibration approach' is used, the accuracy for a targeted species will be computed from a quadratic propagation of errors originating from the certification of the gas standard and the dilution unit,

$$RSD\ (accuracy) = \sqrt{\left(\frac{\sigma_{CAL}}{VMR_{CAL}}\right)^2 + \frac{1}{(F_{CAL}+F_{AIR})^2}\left(\frac{F_{AIR}{}^2}{F_{CAL}{}^2} \times \sigma_{F_{CAL}}^2 + \sigma_{F_{AIR}}^2\right)} \qquad \text{Eq. 7}$$

Where σ_{CAL}, $\sigma_{F_{CAL}}$ and $\sigma_{F_{AIR}}$ are 1-sigma uncertainties associated to the targeted compound volume mixing ratio in the calibration mixture, the flow rate of the calibration mixture and the flow rate of dilution air, respectively. VMR_{CAL}, F_{CAL} and F_{AIR} are the targeted compound volume mixing ratio in the calibration mixture, the flow rate of the calibration mixture and the flow rate of dilution air. The uncertainty associated to the quantification of the protonated VOC signal is not factored in Eq.7 since the large signal-to-noise ratio observed during calibration experiments leads to a negligible contribution of this source of errors.

Example: *A certified gas mixture is used to calibrate the acetone signal (m/z 59.049). The calibration mixture certificate indicates an extended (i.e. 2σ) relative error of 5% on the stated acetone mixing ratio of 1 ppmv. A dilution system made of 2 mass flow controllers allows reaching a dilution factor of 100 by mixing 10 SCCM of the calibration mixture with 990 SCCM of zero air. 1σ relative uncertainties on flow rates are estimated to be 2% and 1% for the calibration gas and zero air, respectively.*

What is the calibration accuracy for acetone?

The relative 1σ accuracy will be 3.3% using Eq. 7, with $\frac{\sigma_{CAL}}{VMR_{CAL}} = 2.5\%$, $\frac{1}{(F_{CAL}+F_{AIR})^2}\left(\frac{{F_{AIR}}^2}{{F_{CAL}}^2} \times \sigma_{F_{CAL}}^2 + \sigma_{F_{AIR}}^2\right) = 4.9\times10^{-5}$.

(ii) If the 'kinetic approach' is used, the accuracy will depend on the following

a. For species present in the calibration gas, the accuracy can be estimated as for the 'calibration approach',

b. For identified species not present in the calibration gas whose proton transfer rate constants are known, a relative accuracy of approximately 30% (2σ) has recently been estimated during the PICAB study.[9] The stated accuracy is only valid if the parent ion fragmentation is well accounted for, interferences from the fragmentation of higher m/z protonated compounds are negligible, de-protonation reactions are of minor significance (i.e., the VOC's proton affinity is significantly higher than that of water), and surface effects (such as those from the sampling line or PTR-MS inlet) are negligible,

c. For unidentified species, the use of a proton transfer rate constant of $3\times10^{-15} m^3 s^{-1}$ as recommended in the principle section will lead to an accuracy of approximately 65% (2σ), assuming a true rate constant in the range of $2\text{-}4\times10^{-15} m^3 s^{-1}$. This estimation is valid under the conditions of negligible fragmentation of the parent ion, no interferences from the fragmentation of higher m/z protonated compounds, and no de-protonation reactions.

Limit of detection – This figure of merit is derived from blank measurements for each targeted species and can be computed as follows:

$$LOD = 3 \times \frac{\sqrt{C_{AH^+}^{blank}}}{S_m(AH^+)} \qquad \text{Eq. 8}$$

$C_{RH^+}^{blank}$ and $S_m(AH^+)$ are expressed in units of counts and counts $ppbv^{-1}$, respectively. In contrast to $S_N(AH^+)$ used in Eqs. 2 and 3, $S_m(AH^+)$ is the unnormalized sensitivity, which is retrieved from calibrations using either the 'calibration' (Eq. 9) or 'kinetic' (Eq. 10) approaches.

$$S_m(RH^+) = \frac{S_N(AH^+) \times \left(C_{H_3O^+} + Xr \times C_{H_3O^+(H_2O)}\right)}{10^6} \qquad \text{Eq. 9}$$

$$S_m(RH^+) = \frac{T_{AH^+}}{T_{H_3O^+}} \times \frac{d \times k}{\mathrm{K}_0 \times N_0} \times \frac{N^2}{E} \times C_{H_3O^+} \qquad \text{Eq. 10}$$

It is important to note that Eq. 8 is only valid when $C_{AH^+}^{blank}$ exceeds a threshold of 5 counts, which is needed to ensure a symmetric Poisson distribution. If $C_{AH^+}^{blank}$ values below 5 counts are observed at the selected time resolution, signals should be integrated over a longer period to accumulate blank signals above 5 counts, allowing for an accurate estimation of the LoD at this extended integration time. The LoD at the initial time resolution can then be determined using the square root law, which states that the standard deviation of the mean decreases in proportion to the square root of the number of samples.

Example: *On the basis of the example given above for precision calculations, let's assume that the unnormalized sensitivity $S_m(AH^+)$ is 200 counts $ppbv^{-1}$ for the species of interest at a measurement time resolution of 0.5 s.*

What is the detection limit for ambient measurements of the targeted species?

The LOD for measurements performed at a time resolution of 0.5 s would be 34 pptv ($3\times\sqrt{5}/200$ ppbv). If 1-minute average values are computed, the blank signal and sensitivity would be 600 cts and 24000 cts $ppbv^{-1}$, which leads to a LOD of 3 pptv ($3\times\sqrt{600}/24000$ ppbv).

4. Field operation

Ideally the PTR-MS should be operated in an air-conditioned room. If this is not feasible, the frequency of calibrations and blank measurements indicated in section 3 should be increased, as variations in temperature can cause instrumental drifts.

An example of recommended setup is shown in Fig. 1, where a distinction is made between the PTR-MS inlet (usually provided with the instrument, in orange in Fig.1) and the sampling line (blue). In this setup, the use of solenoid valves allows alternating between "blank or calibration" modes and ambient measurements. For the former, zero air with the option for diluted calibration gas is provided to the front tip of the PTRMS inlet through a constantly flushed piece of tubing connected to a multiport solenoid Valve. With this setup, potential artefacts from the PTRMS inlet can be characterized via zeroing as described in section 3a. The direct addition of diluted calibration gas allows on-site calibrations as outlined in section 3b, while also facilitating the assessment of instrumental response times for specific compounds at known volume mixing ratios. This inlet-tubing response assessment should be conducted monthly.

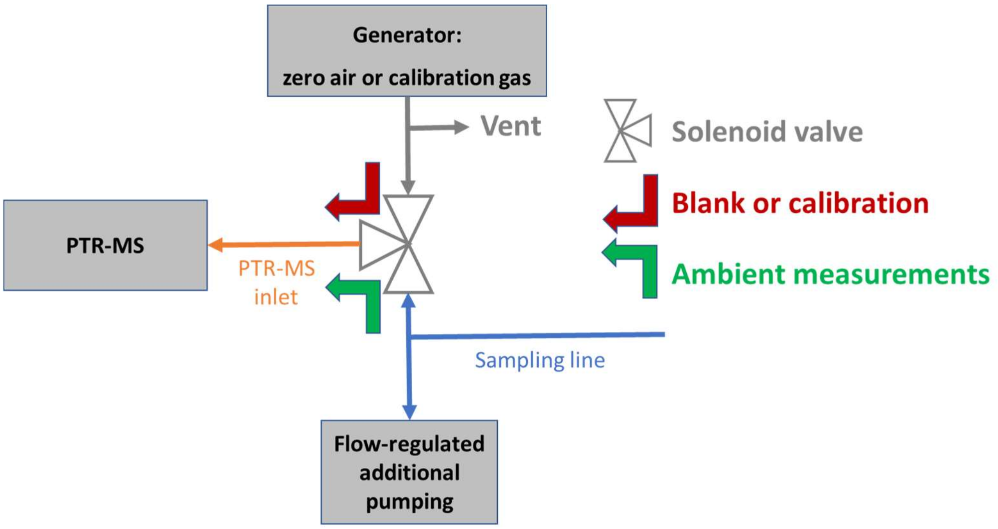

Figure 1:

PTR-MS setup for field operation

a. Sampling

For field measurements, an ideal sampling system (sampling line + PTR-MS inlet, see Fig. 1) delivers the sample into the drift tube without changing its composition. In practice, contact between sample and materials cannot be avoided but should be minimized. This section provides information to transfer ambient air into the PTR-MS drift tube and recommends materials and operating conditions (temperature, flow rate) that should be used for sampling lines.

The sampling height has to be carefully chosen to provide an air sample representative of the surrounding area (type of vegetation, orography, soil, water, snow) (ACTRIS deliverable WP4/D4.9 v.2014/09/30). If possible, VOCs should be measured at 2-3 different heights for a significant period of time to determine which inlet height is suitable. Recommended materials include coated stainless steel (Silcosteel or SilcoNert®1000 and Sulfinert or SilcoNert®2000) preferably, or polymer after a sufficient passivation time before use (PFA, PTFE). As recommended for other VOC measurement techniques (ACTRIS deliverable WP4/D4.9 v.2014/09/30), untreated stainless steel should not be used. The sampling line can be slightly heated to reduce VOC sorption effects. Measurements of compounds exhibiting a good thermal stability such as those reported in Table 1 can be performed with a sampling line heated to 40-50°C. If low-volatility compounds such as IVOC and SVOC are targeted, the temperature can be increased up to 80°C. It is important to ensure that there is no cold spot in the sampling line to avoid condensation of water and the loss of low-volatility or high-solubility VOCs. The later needs to be carefully considered if the instrument is housed in an air-conditioned unit where the temperature is lower than in ambient air.

Typical inner diameters of the sampling lines are in the range 2-12 mm and the length will depend on the measurement height and place. Generally, the sampling line should be as short as possible and the flow rate should be high enough (a few L/min to a few tens of L/min) to reduce the residence time below a few seconds. For this purpose, additional pumping capabilities are usually required (see Fig. 1) since the drift tube flow rate is usually ranging from a few tens to a few hundreds of mL/min. It is important to note that the sample residence time in the tubing is not well defined under laminar flow conditions (the flow speed declines close to the tubing walls), therefore operation under turbulent flow conditions (Reynold number above 3000) is preferable – if feasible – at the expanse of a pressure drop in the line.

Example: *A 50m sampling line with an inner diameter of 7mm operated at a flow rate of 30L/min will provide a Reynold number above 6000, ensuring turbulent conditions, and a residence time below 4 seconds under normal conditions (1013 hPa, 20°C). There is a significant pressure drop under these conditions, but the pressure at the exit of the tube (~600 hPa) should be sufficient to maintain the required pressure in the drift tube. So, a residence time below 5 seconds should be achievable for virtually any field setup.*

The entrance of the sampling line should be protected from precipitation and a particle filter (mesh size < 5 µm) should be placed at the top of the line and exchanged regularly (ACTRIS deliverable WP4/D4.9 v.2014/09/30). However, if low volatility compounds are targeted, the particle filter can be omitted to avoid losses and memory effects, with the drawback of potential clogging of capillaries inside the instrument.

When PTR-MS are coupled to laboratory apparatus such as atmospheric simulation chambers, there is no need of additional pumping unless the sampling line is longer than 2 meters. Recommendation is to use sampling lines as short as possible. The use of a particle filter is not needed.

b. Operating conditions

Commonly used operating conditions for drift tubes are reported in Table 4. Regarding E/N, values lower than 120 Td could be used in some applications where the VOC ion fragmentation is too large. However, when using low E/N values, the user should thoroughly characterize any potential humidity dependencies of the PTR-MS response, especially for compounds with low proton affinity.

When operating conditions have been selected for ambient measurements, fragmentation ratios of targeted VOCs should be verified as discussed in section 3b.

Tuning of the ion source and the mass spectrometer, including ion guides if present, should be performed as recommended by the provider. Only recommendations on criteria that should be met after an optimization are given in Table 5. Reagent ion purity and distribution can be evaluated as described in Annex 7.

Table 4: Field operating conditions

Parameter	Range	Comments
Temperature (°C)	50-60 (up to 80 if IVOC & SVOC are targeted)	This temperature should be kept higher than that of the PTRMS-inlet to prevent condensation. Higher temperature: less memory effects and improved response time, less losses of semi-volatile VOCs.
Pressure (mbar)	1-4	Higher pressure reduces the diffusion of sampled air into the ion source in certain PTR-MS models, resulting in lower impurity levels of O_2^+ and NO^+
E/N (Td)	120-140	A higher E/N reduces the abundance of $H_3O^+(H_2O)$ but increases the fragmentation of protonated VOCs
PTR-MS inlet Sampling flow rate (SCCM)	50-500	A higher flow rate reduces the impact of instrument related contamination on blank signals
Sampling line flow rate	See section 4.a	A higher flow rate reduces the impact of sampling line related contamination on blank signals

Table 5: Criteria for optimum tuning of the ion source/drift tube

Ion source	
Primary ions purity	$[O_2^+ + NO^+] < 3\%$ of $[H_3O^+ + H_3O^+(H_2O)]$
Primary ions distribution	$[H_3O^+(H_2O)] < 20\%$ of $[H_3O^+ + H_3O^+(H_2O)]$

c. Checking for proper field operation

When ambient measurements are ongoing, several metrics should be checked daily to ensure proper operation of the PTR-MS instrument. These metrics, reported in Table 6, should be displayed in control charts to quickly identify any deviations as specified in the Criteria column. If deviations are observed, instruments should be tuned as advised by the manufacturer to solve the specific issues.

Table 6: Control metrics for proper field measurements

Metric	Purpose	Criteria
H_3O^+ ion signal at m/z 21.022	Check cleanliness of reagent ion source and/or a change in detection sensitivity	Not lower than 70% of initial value at installation
$[O_2^+ + NO^+] / [H_3O^+ + H_3O^+(H_2O)]^*$	Check for reagent ions purity	As defined in Table 5
$[H_3O^+(H_2O)] / [H_3O^+ + H_3O^+(H_2O)]^*$	Check for reagent ions distribution	As defined in Table 5
R_{FWHM} (section 3c) & Peak shape	Check ToFMS tuning	R_{FWHM} not lower than 70% of initial value at installation
Blank values (sections 3a & 4b)	Check for leaks and/or contamination	Lower than 1.3 times initial values at installation
N_2H^+ ion signal at m/z 29.014	Check collision energetics in transfer region - N_2H^+ and CO_2H^+ only formed via endothermic reactions in transfer system	Minimize at selected ion-source/drift operating conditions
CO_2H^+ ion signal at m/z 44.998		
Fragmentation reference species** Ex: Diiodobenzene - ratio of m/z 203.943 over m/z 330.848	Check for abnormal ion fragmentation	Deviation lower than 30% from initial value at installation

** Ratios of transmission corrected signals. **Reference compounds continuously added to the drift tube such as diiodobezene in the PerMaScale feature of IONICON instruments*

5. Data extraction: Retrieval of ambient VMR from mass spectra & reporting

Software tools provided with PTR-MS (PTR-MS Viewer or Ionicon Data Analyzer from IONICON Analytic GmbH, Tofware from TOFWERK) or by the scientific community (Toftool,[14] PTRwid[15]) can be used to automate data extraction. Below we outline the general procedure used to retrieve VMR from the recorded mass spectra. The reader is referred to manuals or published scientific papers for details on specific extended processing using the abovementioned software.

The following steps are required and are usually configurable by the user in the software:

- ***Mass scale calibration –*** This step allows the conversion of recorded ion time-of-flight values into ion masses (m/z). A good mass accuracy is needed during this step to unambiguously determine atomic composition of detected ions as discussed in section 3c.

  The mass calibration procedure requires the selection of several reference peaks at known exact m/z and with a sufficient signal-to-noise ratio, i.e. single isobaric compounds in the 100 to 10.000 cps range. The selected peaks have to be present on all mass spectra, including both ambient and blank measurements. Table 7 reports reference peaks that are commonly used to perform mass calibrations when H_3O^+ is the reagent ion. Ideally the reference peaks will encompass all m/z values targeted for ambient measurements. This usually requires the continuous addition of high molecular weight compounds into the drift reactor (for instance PerMaScale feature on IONICON instruments – addition of diiodobenzene detected at m/z 330.848 and 203.943). The use of a PerMaScale-like system is highly recommended.

Table 7: Reference peaks for mass calibration

Species	Formula	m/z (Da)	Comments
Hydronium	$H_3{}^{18}O^+$	21.022	
Hydronium water-cluster	$H_3{}^{16}O^+(H_2{}^{16}O)$	37.028	May be saturated
Acetone.H$^+$	$C_3H_6O.H^+$	59.049	May be missing when blank measurements are performed
Diiodobenzene.H$^+$ and fragment	$C_6H_4I_2.H^+$	330.848	PerMaScale feature from IONICON instruments
	fragment	203.943	

- ***Peak-shape analysis and peak-fitting –*** Mass resolution[a] should be quantified over the m/z range of interest to ensure that an optimum deconvolution of peaks can be performed at each mass unit (for instance, Δm/m>3500 allows an unambiguous identification of $C_xH_yO_z{}^+$ ions for m/z>40).[16] A list of isobaric species present within each mass bin of interest (known as peak list, similar to the table shown in Annex 1) is compiled and used to constrain the peak-fitting procedure, using either (i) a simple window whose boundaries are set to encompass an isolated individual peak (Fig. 2a) or (ii) a multipeak analysis allowing the deconvolution of overlapping peaks (Fig. 1b).

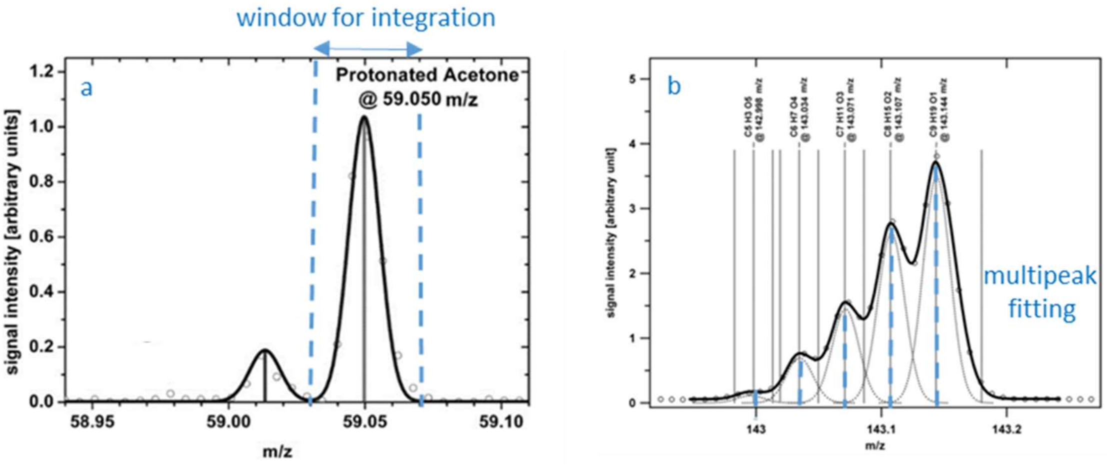

Figure 1: Peak-fitting. Integration of the peak signal within predefined boundaries (Panael a) or using a multipeak fitting procedure (Panel b). Adapted from Graus et al.[16]: PTR-ToFMS instrument exhibiting a mass resolution of approximately 4200 and 4500 at 59 and 143 m/z, respectively.

- ***Conversion to VMR –*** Integrated ion signals, extracted from the previous step for each peak of interest, are plugged into Eqs. 1 or 3 for the 'kinetic' or 'calibration' approaches (section 3b), respectively. For the 'kinetic approach', all parameters included in Eq. 1 are constrained as discussed in section 2. In practice, most PTR-MS software mentioned above integrate functions to automate the VMR calculations. Corrections for humidity effects can be applied if humidity-dependent responses are observed as discussed in section 3b. If the parent ion fragments at a known rate, VMR of fragments are also computed or a correction can be applied to retrieve unbiased VMR as shown in Eq. 1 and discussed in section 3b.

For the calibration approach, analyte signals have to be normalized using (i) H_3O^+ as shown in Eq. 2 if the PTR-MS response is not humidity dependent or (ii) both reagent ions (H_3O^+, $H_3O^+(H_2O)$) and calibrated values of X_r as shown in Eq. 3 and discussed in section 3b is a humidity dependence is observed. The normalized signals are then converted into VMR using normalized sensitivity factors $S_N(AH^+)$.

- ***Blank subtraction –*** Most software mentioned above to process mass spectra do not allow an automated subtraction of blanks and this step has to be performed manually. The above procedure provides VMR values for both ambient and blank measurements, the later performed as described in sections 3a. VMR values for blanks are either averaged or interpolated between each blank measurement and subtracted from ambient VMR values.

- ***Reporting of VMR –*** Ions detected at different m/z will be reported using the nomenclature described on the EBAS web site[c]. When a compound's name can be unambiguously attributed to a specific m/z, the exact name will be used for reporting (e.g. methanol, acetonitrile, ethanal, etc.). When isomers (or isobars for PTR-QMS) are detected together, the following will be used for reporting : "mass_XX_organic_compounds". It is worth noting that in EBAS, groups of isomers (or isobars for PTR-QMS) will be associated with an additional definition text of the variable, which will contain the list of species contained in the group.

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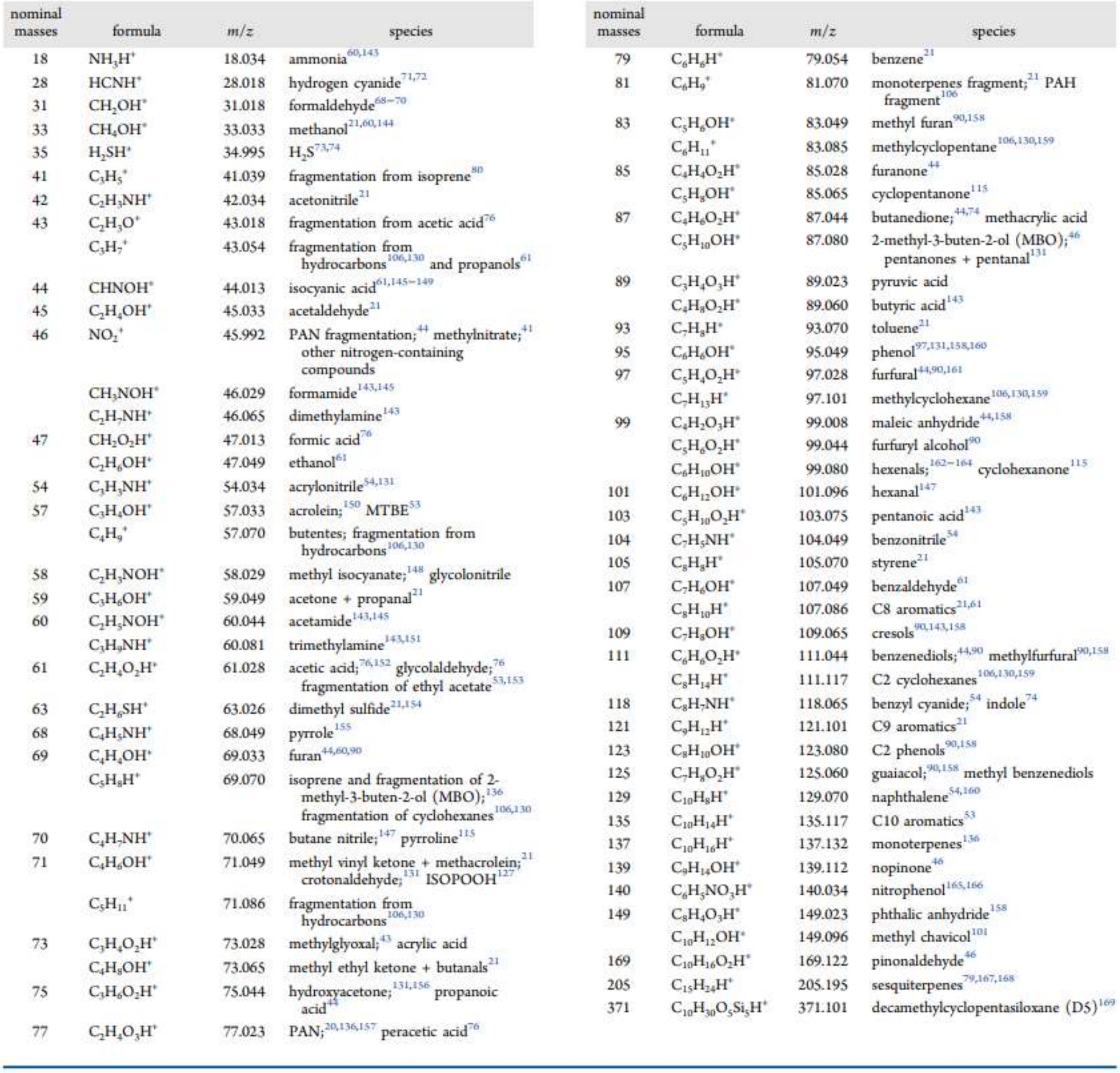
Annex 1: Non-exhaustive list of compounds detected at specific m/z values

Table A1.1: *Table 2 from Yuan et al.[1] - Identified Compounds for Mass Lists on PTR-MS*



nominal masses	formula	*m/z*	species
18	NH_3H^+	18.034	ammonia[60,143]
28	$HCNH^+$	28.018	hydrogen cyanide[71,72]
31	CH_2OH^+	31.018	formaldehyde[68−70]
33	CH_4OH^+	33.033	methanol[21,60,144]
35	H_2SH^+	34.995	H_2S[73,74]
41	$C_3H_5^+$	41.039	fragmentation from isoprene[80]
42	$C_2H_3NH^+$	42.034	acetonitrile[21]
43	$C_2H_3O^+$	43.018	fragmentation from acetic acid[76]
	$C_3H_7^+$	43.054	fragmentation from hydrocarbons[106,130] and propanols[61]
44	$CHNOH^+$	44.013	isocyanic acid[61,145−149]
45	$C_2H_4OH^+$	45.033	acetaldehyde[21]
46	NO_2^+	45.992	PAN fragmentation;[44] methylnitrate;[41] other nitrogen-containing compounds
	CH_3NOH^+	46.029	formamide[143,145]
	$C_2H_7NH^+$	46.065	dimethylamine[143]
47	$CH_2O_2H^+$	47.013	formic acid[76]
	$C_2H_6OH^+$	47.049	ethanol[61]
54	$C_3H_3NH^+$	54.034	acrylonitrile[54,131]
57	$C_3H_4OH^+$	57.033	acrolein;[150] MTBE[53]
	$C_4H_9^+$	57.070	butentes; fragmentation from hydrocarbons[106,130]
58	$C_2H_3NOH^+$	58.029	methyl isocyanate;[148] glycolonitrile
59	$C_3H_6OH^+$	59.049	acetone + propanal[21]
60	$C_2H_5NOH^+$	60.044	acetamide[143,145]
	$C_3H_9NH^+$	60.081	trimethylamine[143,151]
61	$C_2H_4O_2H^+$	61.028	acetic acid;[76,152] glycolaldehyde;[76] fragmentation of ethyl acetate[53,153]
63	$C_2H_6SH^+$	63.026	dimethyl sulfide[21,154]
68	$C_4H_5NH^+$	68.049	pyrrole[155]
69	$C_4H_4OH^+$	69.033	furan[44,60,90]
	$C_5H_8H^+$	69.070	isoprene and fragmentation of 2-methyl-3-buten-2-ol (MBO);[136] fragmentation of cyclohexanes[106,130]
70	$C_4H_7NH^+$	70.065	butane nitrile;[147] pyrroline[115]
71	$C_4H_6OH^+$	71.049	methyl vinyl ketone + methacrolein;[21] crotonaldehyde;[131] ISOPOOH[127]
	$C_5H_{11}^+$	71.086	fragmentation from hydrocarbons[106,130]
73	$C_3H_4O_2H^+$	73.028	methylglyoxal;[43] acrylic acid
	$C_4H_8OH^+$	73.065	methyl ethyl ketone + butanals[21]
75	$C_3H_6O_2H^+$	75.044	hydroxyacetone;[131,156] propanoic acid[44]
77	$C_2H_4O_3H^+$	77.023	PAN;[20,136,157] peracetic acid[76]
79	$C_6H_6H^+$	79.054	benzene[21]
81	$C_6H_9^+$	81.070	monoterpenes fragment;[21] PAH fragment[106]
83	$C_5H_6OH^+$	83.049	methyl furan[90,158]
	$C_6H_{11}^+$	83.085	methylcyclopentane[106,130,159]
85	$C_4H_4O_2H^+$	85.028	furanone[44]
	$C_5H_8OH^+$	85.065	cyclopentanone[115]
87	$C_4H_6O_2H^+$	87.044	butanedione;[44,74] methacrylic acid
	$C_5H_{10}OH^+$	87.080	2-methyl-3-buten-2-ol (MBO);[46] pentanones + pentanal[131]
89	$C_3H_4O_3H^+$	89.023	pyruvic acid
	$C_4H_8O_2H^+$	89.060	butyric acid[143]
93	$C_7H_8H^+$	93.070	toluene[21]
95	$C_6H_6OH^+$	95.049	phenol[97,131,158,160]
97	$C_5H_4O_2H^+$	97.028	furfural[44,90,161]
	$C_7H_{13}H^+$	97.101	methylcyclohexane[106,130,159]
99	$C_4H_2O_3H^+$	99.008	maleic anhydride[44,158]
	$C_5H_6O_2H^+$	99.044	furfuryl alcohol[90]
	$C_6H_{10}OH^+$	99.080	hexenals;[162−164] cyclohexanone[115]
101	$C_6H_{12}OH^+$	101.096	hexanal[147]
103	$C_5H_{10}O_2H^+$	103.075	pentanoic acid[143]
104	$C_7H_5NH^+$	104.049	benzonitrile[54]
105	$C_8H_8H^+$	105.070	styrene[21]
107	$C_7H_6OH^+$	107.049	benzaldehyde[61]
	$C_8H_{10}H^+$	107.086	C8 aromatics[21,61]
109	$C_7H_8OH^+$	109.065	cresols[90,143,158]
111	$C_6H_6O_2H^+$	111.044	benzenediols;[44,90] methylfurfural[90,158]
	$C_8H_{14}H^+$	111.117	C2 cyclohexanes[106,130,159]
118	$C_8H_7NH^+$	118.065	benzyl cyanide;[54] indole[74]
121	$C_9H_{12}H^+$	121.101	C9 aromatics[21]
123	$C_8H_{10}OH^+$	123.080	C2 phenols[90,158]
125	$C_7H_8O_2H^+$	125.060	guaiacol;[90,158] methyl benzenediols
129	$C_{10}H_8H^+$	129.070	naphthalene[54,160]
135	$C_{10}H_{14}H^+$	135.117	C10 aromatics[53]
137	$C_{10}H_{16}H^+$	137.132	monoterpenes[136]
139	$C_9H_{14}OH^+$	139.112	nopinone[46]
140	$C_6H_5NO_3H^+$	140.034	nitrophenol[165,166]
149	$C_8H_4O_3H^+$	149.023	phthalic anhydride[158]
	$C_{10}H_{12}OH^+$	149.096	methyl chavicol[101]
169	$C_{10}H_{16}O_2H^+$	169.122	pinonaldehyde[46]
205	$C_{15}H_{24}H^+$	205.195	sesquiterpenes[79,167,168]
371	$C_{10}H_{30}O_5Si_5H^+$	371.101	decamethylcyclopentasiloxane (D5)[169]

Annex 2: Equilibration time required for zeroing the instrument

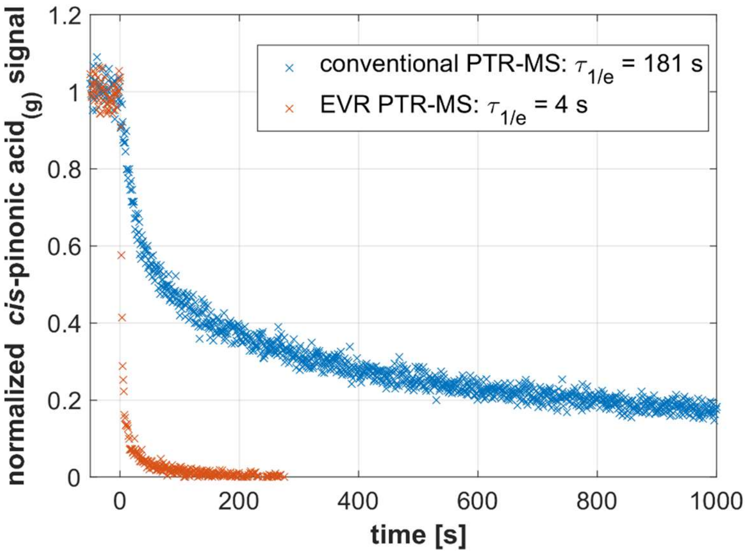


Figure A2.1: Comparison of equilibration times for a semi-volatile species (cis-pinonic acid) between a traditional PTR-MS instrument with Peek inlet capillaries (blue trace) and an instrument optimized for fast responses (PFA and Sulfinert only, coating of the inner surface of the drift tube to avoid losses of low-volatility species – red trace).

Reference: Piel, F., Müller, M., Winkler, K., Skytte af Sätra, J., and Wisthaler, A.: Introducing the extended volatility range proton-transfer-reaction mass spectrometer (EVR PTR-MS), Atmos. Meas. Tech., **14**, 1355–1363 (2021).

Annex 3: NPL gas standard

Table A2.1. *Composition of the NPL standard.*

Compound	Formula	Protonated mass(es)	Fragments
Nitrogen (balance)	N_2	-	-
Methanol	CH_4O	33.033	-
Acetonitrile	CH_3CN	42.034	-
Acetaldehyde	C_2H_4O	45.033	-
Ethanol	C_2H_6O	47.050	29.039
Acetone	C_3H_6O	59.049	
Dimethyl sulfide	C_2H_6S	63.030	
Isoprene	C_5H_8	69.070	41.039
Methylvinylketone (3-buten-2-one)	C_4H_6O	71.049	
Methylethylketone (Butan-2-one)	C_4H_8O	73.065	
Benzene	C_6H_6	79.054	
Toluene	C_7H_8	93.070	
m-Xylene	C_8H_{10}	107.086	
1,2,4-Trimethylbenzene	C_9H_{12}	121.101	
1,2,4-Trifluorobenzene	$C_6H_3F_3$	133.026	
3-Carene	$C_{10}H_{16}$	137.132,	81.070
1,2,4-Trichlorobenzene	$C_6H_3Cl_3$	180.937, 182.934, 184.931	
Hexamethylcyclotrisiloxane (D3)	$C_6H_{18}Si_3O_3$	223.064, 224.063, 225.061	207.032, 208.032, 209.029
Octamethylcyclotetrasiloxane (D4)	$C_8H_{24}Si_4O_4$	297.083, 298.082, 299.079	281.051, 282.051, 283.048
Decamethylcyclopentasiloxane (D5)	$C_{10}H_{30}Si_5O_5$	371.101, 372.101, 372.105, 373.098	355.070, 356.070, 357.067
Perfluorotributylamine	$C_{12}F_{27}N$	671.968	413.977

Additional information can be found in the following reference:

Worton, D. R., Moreno, S., O'Daly, K., Holzinger, R.: Development of an SI-traceable transmission curve reference material to improve comparability of proton transfer reaction mass spectrometry measurements, Atmospheric Meas. Tech., **16**, 1061–1072 (2023)

Annex 4: Examples of ion transmission curves

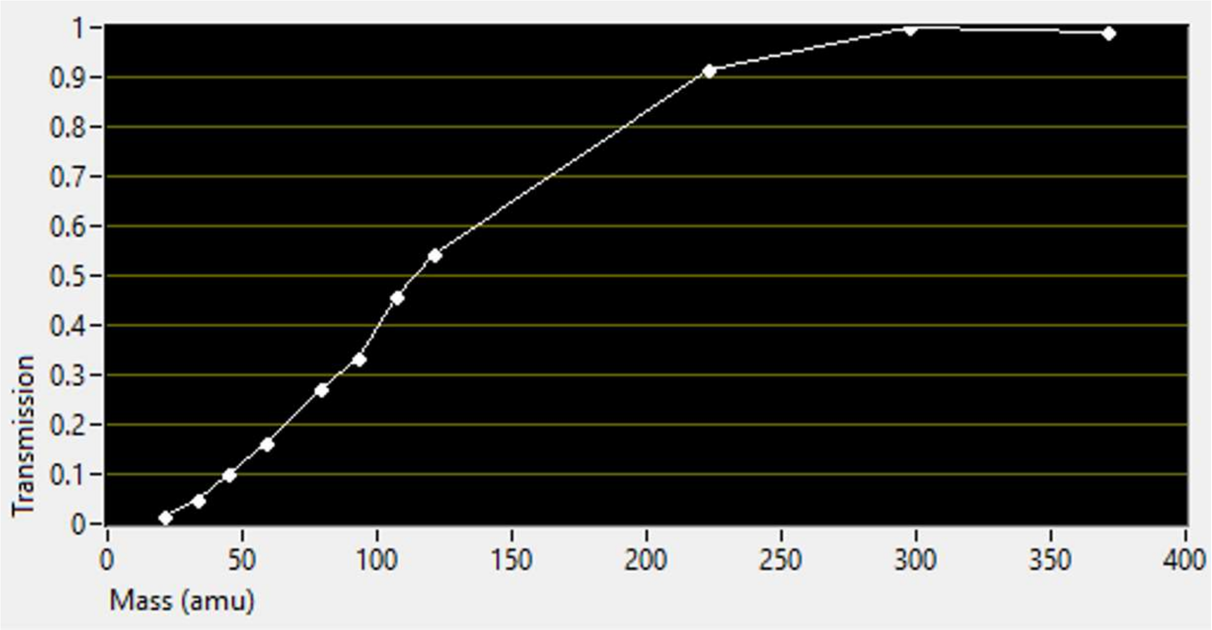


Figure A3.1: Well-defined transmission function exhibiting a smoothly increasing concave trend that gradually stabilizes into a plateau.

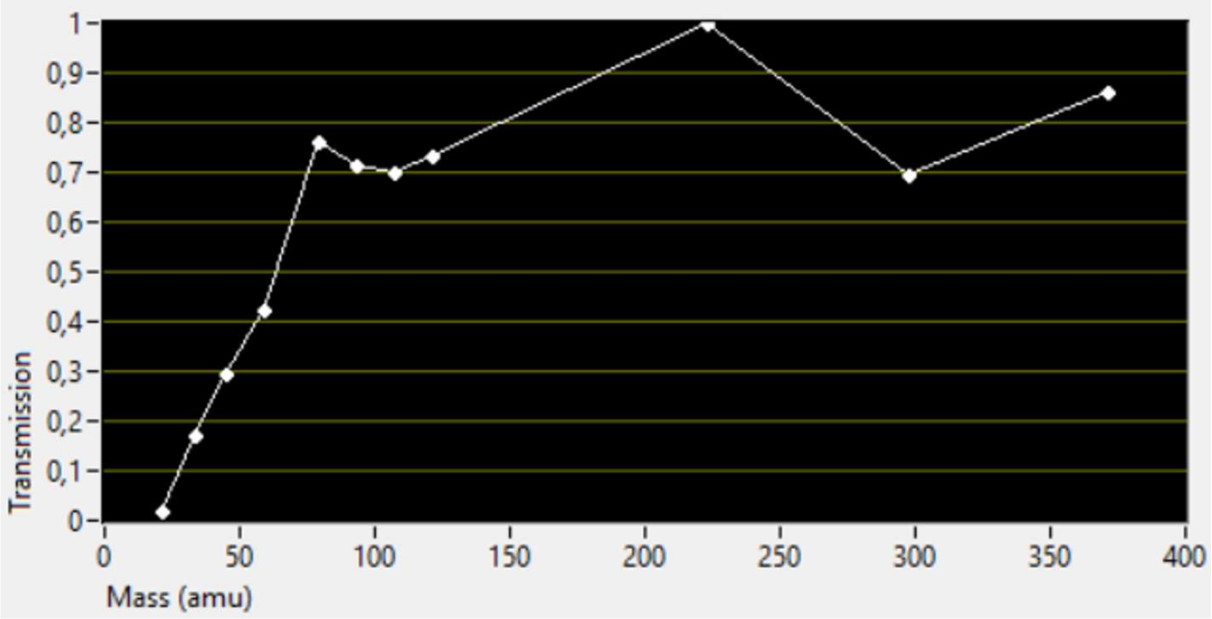


Figure A2.1: Poor transmission function displaying noticeable outliers.

Annex 5: Examples of humidity-dependent sensitivities

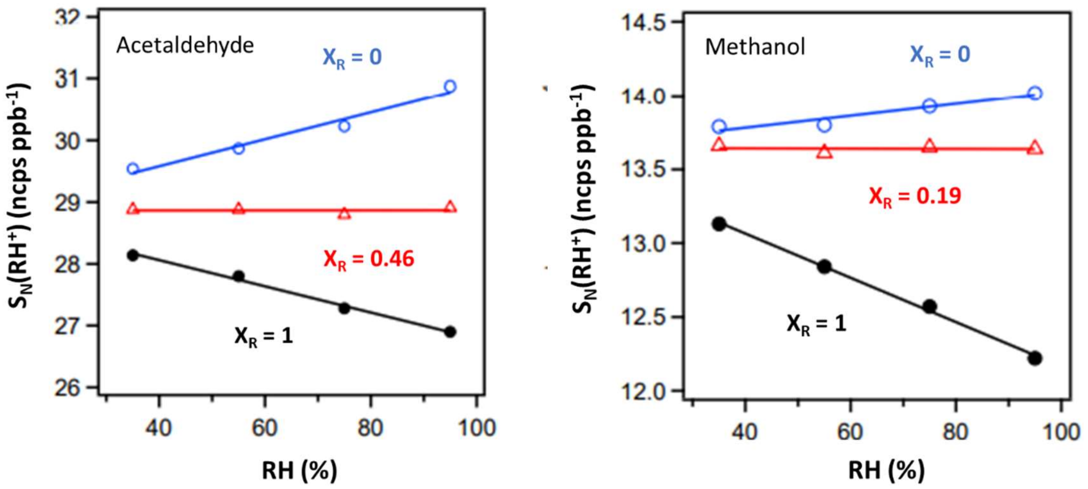


Figure A6.1: *Determinations of Xr and SN(AH+) values for a second-generation KORE INC. PTR-ToFMS using the ‘calibration’ approach. Left: Acetaldehyde $S_N(AH^+)$=28.9 ncps $ppbv^{-1}$ & X_R=0.46. Right: Methanol SN(AH+)=13.6 ncps $ppbv^{-1}$ & X_R=0.19. RH measured at 20°C.*

Annex 6: Detector voltage optimization

Instrument equipped with a ***Time to Digital Converter (TDC)*** - To determine the optimum setting for the detector's voltage, the user should pass the calibration gas to the instrument and monitor how the signal detected at the highest m/z increases with a change of + 50V in the detector's voltage. If the ion signal increases by more than 20%, the user should continue to increase the voltage by steps of +50V until the relative change in signal is lower than 20%. At that stage, the detector's voltage should be brought back to the previous voltage (i.e. actual voltage minus 50V).

Instrument equipped with an ***Analog to Digital Converter (ADC)*** – The optimum setting is set by adjusting the MCP voltage (as above) to regain the single ion signal (mV.ns) the manufacturer recommends.

Annex 7: Evaluation of primary ion purity and distribution

Primary ion purity

In addition to H_3O^+, spurious reagent ions can be produced in the ion source (O_2^+ and NO^+) and formed in the drift reactor when H_3O^+ clusters with water ($H_30^+.H_2O$). As mentioned in Table 5, the amounts of O_2^++NO^+ and $H_3O^+.H_2O$ compared to H_3O^+ should be lower than 3% and 20%, respectively. Two different approaches are described below to check that these criteria are met:

1st approach: Monitoring ratios of transmission-corrected signals for O_2^+/H_30^+, NO^+/H_3O^+ and $H_3O^+.H_2O/ H_30^+$.

$$\frac{O_2^+}{H_3O^+} = \left(\frac{C_{O_2^+}^{33.994}}{T_{O_2^+}^{33.994}}\right) \bigg/ \left(\frac{C_{H_3O^+}^{21.022}}{T_{H_3O^+}^{21.022}} \times 2\right) \qquad \frac{NO^+}{H_3O^+} = \left(\frac{C_{NO^+}^{29.998}}{T_{NO^+}^{29.998}}\right) \bigg/ \left(\frac{C_{H_3O^+}^{21.022}}{T_{H_3O^+}^{21.022}} \times 487\right)$$

$$\frac{H_3O^+.H_2O}{H_3O^+} = \left(\frac{C_{H_3O^+.H_2O}^{37.029}}{T_{H_3O^+.H_2O}^{37.029}}\right) \bigg/ \left(\frac{C_{H_3O^+}^{21.022}}{T_{H_3O^+}^{21.022}} \times 487\right) \quad or \quad = \left(\frac{C_{H_3O^+.H_2O}^{38.033}}{T_{H_3O^+.H_2O}^{38.033}}\right) \times 1.32 \bigg/ \left(\frac{C_{H_3O^+}^{21.022}}{T_{H_3O^+}^{21.022}}\right) \quad or \quad = \left(\frac{C_{H_3O^+.H_2O}^{39.033}}{T_{H_3O^+.H_2O}^{39.033}}\right) \bigg/ \left(\frac{C_{H_3O^+}^{21.022}}{T_{H_3O^+}^{21.022}} \times 2\right)$$

$C_X^{m/Q}$ (counts) is the total signal detected over the measurement duration and $T_X^{m/Q}$ the transmission for species X (X=O_2^+, NO^+, H_3O^+) at the targeted m/z.

2sd approach (recommended): Monitoring the ratio of $C_6H_6^+/C_6H_6.H^+$ ions when calibrating the PTR-MS with a standard mixture containing benzene. This approach allows to infer the total relative amount of O_2^++NO^+ assuming that the ionization of benzene by charge transfer from O_2^+ and NO^+, leading to the formation of $C_6H_6^+$, occurs at the same rate than proton transfer from H_30^+, which leads to the formation of $C_6H_6.H^+$. The equation below does not require to correct ion signals for transmission since $C_6H_6^+$ and $C_6H_6.H^+$ are detected at close m/z.

$$\frac{O_2^+ + NO^+}{H_3O^+} = \frac{C_6H_6^+}{C_6H_6.H^+} = \frac{C_{C_6H_6^+}^{78.047}}{C_{C_6H_6.H^+}^{79.055}}$$

$C_X^{m/Q}$ (counts) is the total signal detected over the measurement duration for species X (X=$C_6H_6^+$, $C_6H_6.H^+$) at the targeted m/z.

It should be noted that the 2sd approach can also be applied using diiodobenzene (when used as internal reference as described in section 5). This species does not fragment in NO^+ and O_2^+ modes and produces an ion at m/z 329.840. Therefore, the ratio of transmission-corrected signals from m/z 329.840 to the sum of m/z 203.943 and m/z 330.848 yields similar as above, eliminating the need to inject a calibration gas.