

**Kinetic and  
thermodynamic  
constraints on I-CIMS  
sensitivity**

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# Constraining the sensitivity of iodide adduct chemical ionization mass spectrometry to multifunctional organic molecules using the collision limit and thermodynamic stability of iodide ion adducts

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## Abstract

The sensitivity of a chemical ionization mass spectrometer (ions formed per number density of analyte) is fundamentally limited by the collision frequency between reagent ions and analyte, known as the collision limit, the ion-molecule reaction time, and the transmission efficiency of product ions to the detector. We use the response of a time-of-flight chemical ionization mass spectrometer (ToF-CIMS) to  $\text{N}_2\text{O}_5$ , known to react with iodide at the collision limit, to constrain the combined effects of ion-molecule reaction time, which is strongly influenced by mixing and ion losses in the ion-molecule reaction drift tube. A mass spectrometric voltage scanning procedure elucidates the relative binding energies of the ion adducts, which influence the transmission efficiency of molecular ions through the electric fields within the vacuum chamber. Together, this information provides a critical constraint on the sensitivity of a ToF-CIMS towards a wide suite of routinely detected multifunctional organic molecules for which no calibration standards exist. We describe the scanning procedure, collision limit determination, and show results from the application of these constraints to the measurement of organic aerosol composition at two different field locations.

## 1 Introduction

The photochemical oxidation of volatile organic compounds (VOC) in the atmosphere generates a wide array of multifunctional organic molecules which contribute to the formation of secondary organic aerosol (SOA), hydroxyl radical sources and sinks, and the cycling and fate of reactive nitrogen. Determination of the identities of these organics, and their abundance in the atmosphere, has remained an analytical challenge because of the inherent complexity of the chemical system, which involves a multitude of precursors and significantly more oxidation products (Goldstein and Galbally, 2007). Chemical ionization mass spectrometry (CIMS) has become increasingly utilized for the measurement of these types of compounds (Bertram et al., 2011; Brophy

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imates from quantum mechanical calculations, along with the experimentally determined collision limit provides an approximate calibration for many compounds in the mass spectrum which would otherwise be impossible to obtain by traditional methods.

## 2 Iodide ToF-CIMS sensitivity to organics

Iodide adduct chemical ionization mass spectrometry has been described in detail previously (Huey et al., 1995; Kercher et al., 2009; Lee et al., 2014). As summarized in Eq. (1), for adduct ionization, there are essentially two components to the instrument sensitivity that will be specific to a molecule: (i) the rate at which product ions are formed via reagent ion-molecule reactions over the fixed interaction time, and (ii) the transmission of the molecular ion to the detector In Eq. (1),  $S_i$  is the sensitivity observed for reaction time  $t$ ,  $k_f$  is the product ion formation rate constant,  $[I^-]$  is the concentration of the reagent ions in the ion molecule region (IMR), and  $T^i$  is the ion-specific transmission efficiency, which depends upon the ion mass-to-charge ( $m/Q$ ), net electric field strength of the transfer optics ( $\varepsilon$ ), and the adduct ion binding energy ( $B^i$ ).

$$S_i = \int_0^t k_f [I^-] dt \times T^i \left( \frac{m}{Q}, \varepsilon, B^i \right) = \text{Product Ion Formation} \times \text{Transmission} \quad (1)$$

A neutral molecule that forms a strongly bound cluster with iodide at the collision limit should be detected with relatively high sensitivity given that it will survive transmission through the ion optics which inherently impart energy to the ions via electric fields. In contrast, a molecule might form an iodide adduct at the collision limit, but be so weakly bound that it is not detected due to collision-induced dissociation (“declustering”) during transit through the vacuum chamber. Thus, knowledge of a cluster’s binding energy and the collision-limited formation rate can provide a means to further constrain the instrument’s sensitivity to a broader range of compounds it detects, even if standards

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Even at our weakest electric field settings, many iodide-organic adducts are partially declustered, and thus the true sigmoidal declustering scan curve is not observed. In these cases, we calculate an effective maximum sensitivity by using a custom non-linear least squares fitting algorithm to determine the extent to which the ion adduct has been declustered during transit through the mass spectrometer's atmospheric pressure interface (API). The fitting algorithm uses a characteristic sigmoidal shape with variable amplitude,  $S_o$ , and location of the voltage at half signal maximum ( $dV_{50}$ ). If there are isomers or isobaric compounds that contribute significantly to the ion signal but have different iodide binding energies, then the declustering scan should not have a sigmoidal shape. While this information could be useful with a highly resolved  $dV$  scan, and is reflected in the fit error, herein we remove ion adducts with mean square residual  $> 10\%$  from the analysis.  $S_o$  is the relative signal that would be detected under weaker electric field strengths than we can operate the instrument ( $dV < 1$  V).  $S_o$  is not a measure of the actual sensitivity, which is generally unknown, but instead is a measure of the extent to which declustering during transmission to the detector affects the actual sensitivity. The  $dV_{50}$  is a measure of relative binding enthalpy. Iodide adducts that are tightly bound survive to higher voltage gradients and therefore have a higher  $dV_{50}$  than more weakly bound adducts.

Pinonic acid (assumed to be measured as the  $C_{10}H_{16}O_3I^-$  ion) is an example of a compound for which a true sigmoidal curve is not observed (see Fig. 3b). The fit for pinonic acid implies that the sensitivity would be enhanced if weaker declustering conditions existed (e.g.  $1.4 = S_o > 1$ ). The sensitivity of the instrument to pinonic acid, calibrated by an authentic standard is  $15 \text{ cps ppt}^{-1}$ , therefore if weaker declustering conditions existed in the instrument, transmission optimized sensitivity for pinonic acid would be  $15 \times 1.4 = 21 \text{ cps ppt}^{-1}$ . This value is near the collision limit determined by calibration to  $N_2O_5$ , which suggests that the iodide-pinonic adduct is formed at near the collision limit in the IMR, but is partially declustered during transit through the ion optics of the mass spectrometer, resulting in a lower observed sensitivity during normal operation settings (e.g.  $S_{\text{obs}} < S_o$ ).

In Fig. 3c we show similar voltage scanning fit results for all iodide-organic adducts (black circles) identified in the mixture produced from  $\alpha$ -pinene ozonolysis in the presence of  $\text{NO}_x$ . We find that  $1/S_o$ , which is related to the maximum possible transmission for each compound, plateaus with increasing  $dV_{50}$ , suggesting that iodide adducts with a  $dV_{50} \sim 6$  V or higher, are sufficiently bound to transit the ion optics without significant declustering losses. Adducts having  $dV_{50} > 6$  V are composed of highly functionalized organics (e.g. Fig. 3c:  $\text{C}_{10}\text{H}_{17}\text{NO}_6$ , black, and  $\text{C}_{20}\text{H}_{32}\text{O}_7$ , green), which is consistent with the stronger bound iodide adducts generally involving one or more hydrogen bonds from a polar hydroxy, hydroperoxy, or carboxylic acid group. We also expect that these compounds are likely formed at near the collision limit as steric effects are unlikely to significantly limit their formation rate, but this hypothesis remains to be tested.

### 2.3 Relationship of $dV_{50}$ to quantum chemical derived binding energies

Figure 4 shows the relationship between iodide adduct binding enthalpies from quantum quantum chemical calculations, the  $dV_{50}$  values determined from the fits to the declustering scans (see also Table 1). Assuming the linear relationship ( $R^2 = 0.92$ ) between the subset of compounds for which we have quantum chemical calculations and experimental determinations holds, the derivation of the binding energy from declustering scans for hundreds of compounds simultaneously is then possible without explicit knowledge of the functional groups or molecular geometry, which is required for quantum calculations. We have shown in a related manuscript that there is a reasonable relationship between theoretical binding enthalpies and measured sensitivity (Iyer et al., 2015). Therefore, by constraining the relationship between quantum calculations and measured scan shape for a subset of compounds, we can use the measured  $dV_{50}$  to estimate the binding enthalpy, and thus instrument sensitivity, for compounds that are too computationally intensive or for which we lack knowledge of molecular structure necessary for optimization. As noted above, the binding enthalpy of an adduct alone does not necessarily determine overall sensitivity. The rate of adduct formation and

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transmission through the mass spectrometer are both important components of the overall sensitivity.

### 3 Application to atmospheric organic aerosol

As an example of the potential application of the above constraints, we apply the collision-limit sensitivity of 22 cps ppt<sup>-1</sup> per million reagent ions to organic compounds detected generally as C<sub>x</sub>H<sub>y</sub>O<sub>z</sub>N<sub>0-1</sub>I<sup>-</sup> upon temperature-programmed thermal desorption of ambient submicron aerosol using a FIGAERO-HRToF-CIMS (Lopez-Hilfiker et al., 2014). We compare the resulting sum total mass loadings of all molecular components with the submicron organic aerosol mass concentrations measured by an aerosol mass spectrometer (AMS) (DeCarlo et al., 2006). Applying the collision-limited sensitivity to all organic iodide adducts to which we have not explicitly calibrated (vast majority of ions), results in a lower limit to mass concentrations measured by the FIGAERO HR-  
ToF-CIMS. Figure 5 shows the result of this comparison for two different locations: (1) a polluted region in the southeast United States (Brent, Alabama), which is dominated by isoprene, and (2) a remote boreal forest site (Hyytiälä, Finland) during springtime which is predominantly influenced by monoterpene emissions. In both locations, the FIGAERO-HRToF-CIMS molecular composition observations explain *at least* 50 % of the total AMS organic mass. That is, based on our declustering scans and distribution of binding enthalpies (e.g. Fig. 3c) from a similar chemical system (e.g.  $\alpha$ -pinene ozonolysis in the presence of NO<sub>x</sub>), we know that not all organic compounds are detected by iodide adduct ionization at the collision limit. It is reasonable to conclude that the underestimate compared to the AMS is because some compounds are detected less sensitively than we assume and not only because there are undetected components. Utilizing the declustering scans during a future field or chamber experiment would provide in situ constraints on how to better apply the collision-limited sensitivity to the mass spectra as illustrated with pinonic acid example above. Based on the results presented in Fig. 5, we conclude that the FIGAERO in combination with iodide adduct

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CIMS is able to detect the majority of oxidized organic molecules that thermally desorb from submicron organic aerosol, thereby providing novel and quantitatively useful constraints on the molecular compositions responsible for SOA formation and growth.

## 4 Conclusions

We present a procedure that allows the determination of the collision-limited sensitivity of an iodide adduct chemical ionization mass spectrometer. We combine this limit with an experimental determination of the binding enthalpies of organic iodide adducts to determine the extent to which collision-induced ion adduct dissociation (i.e. declustering) losses occur during transit through the ion optics of the instrument. We stress that the values of the collision limit or other calibration derived sensitivity values reported herein are likely unique to the electric fields, IMR geometry, pressures, and flows of our instrument. While useful as a relative guide, these values should not be applied to data from other instruments without conducting similar experiments as described here. In the case of adduct formation, steric factors and competitive ligand switching may affect the adduct formation rate, and therefore binding enthalpy alone does not determine sensitivity. For molecules containing a significant number of hydroxy (or hydroperoxy and carboxylic acid) groups, sterics probably play a minor role, so we expect the overall sensitivity to be collision limited and the adduct transmitted to the detector with minimal declustering losses. Many of these types of molecules are impossible to calibrate using traditional methods of authentic standards, but the combination of declustering scanning and collision-limited sensitivity determination allow for reasonable constraints on the instrument response for hundreds of organic molecules which are now routinely detected in the atmosphere.

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We also thank the Cohen group for calibrating the output of our N<sub>2</sub>O<sub>5</sub> calibration source using TD-LIF during the WINTER campaign. This work was supported by the US Department of Energy through awards from the Atmospheric System Research (DOE Grant DE-SC0006867) and NSF (award number AGS-1360745).

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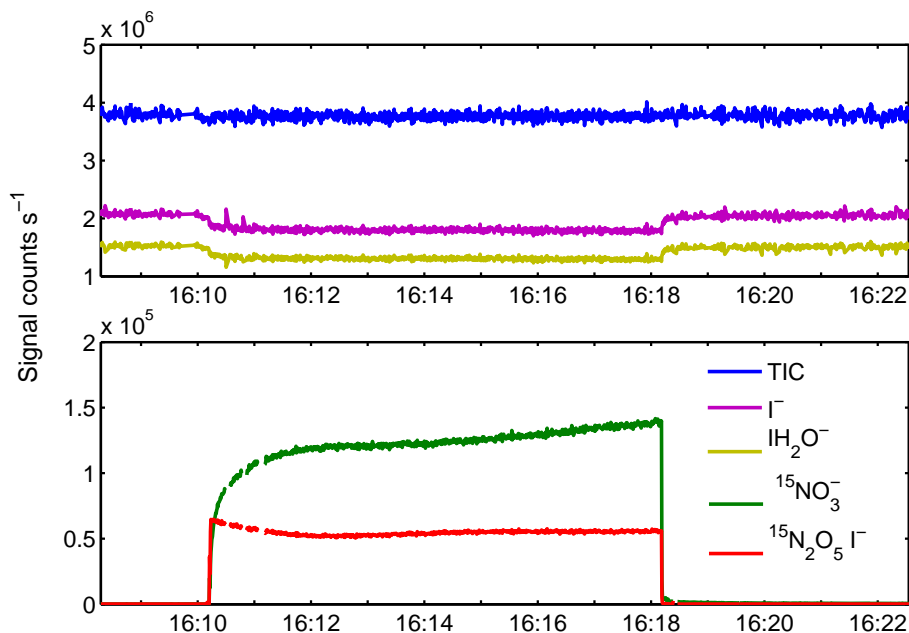
**Table 1.** Compounds used to determine the relationship between  $dV_{50}$  and binding enthalpy derived from quantum calculations (Iyer et al., 2015) at the DLPNO-CCSD(T)//PBE-aug-cc-pVTZ-PP level. The relationship is approximately linear  $R^2 = 0.9$  (see Fig. 4). For details see text.

Compound	Composition	Binding Enthalpy (kcal mol <sup>-1</sup> )	Fit $dV_{50}$ (V)
Glycolic Acid	C <sub>2</sub> H <sub>4</sub> O <sub>3</sub>	-21.1	4.70
Glyoxilic Acid	C <sub>2</sub> H <sub>2</sub> O <sub>3</sub>	-20.8	4.29
Malonic Acid	C <sub>3</sub> H <sub>4</sub> O <sub>4</sub>	-27.8	6.21
Formic Acid	CH <sub>2</sub> O <sub>2</sub>	-23.9	5.80
Acetic Acid	C <sub>2</sub> H <sub>4</sub> O <sub>2</sub>	-17.4	4.10
Succinic Acid	C <sub>4</sub> H <sub>8</sub> O <sub>4</sub>	-27.6	6.19
Nitric Acid	HNO <sub>3</sub>	-22.2	5.50
Nitrous Acid	HONO	-18.7	4.56



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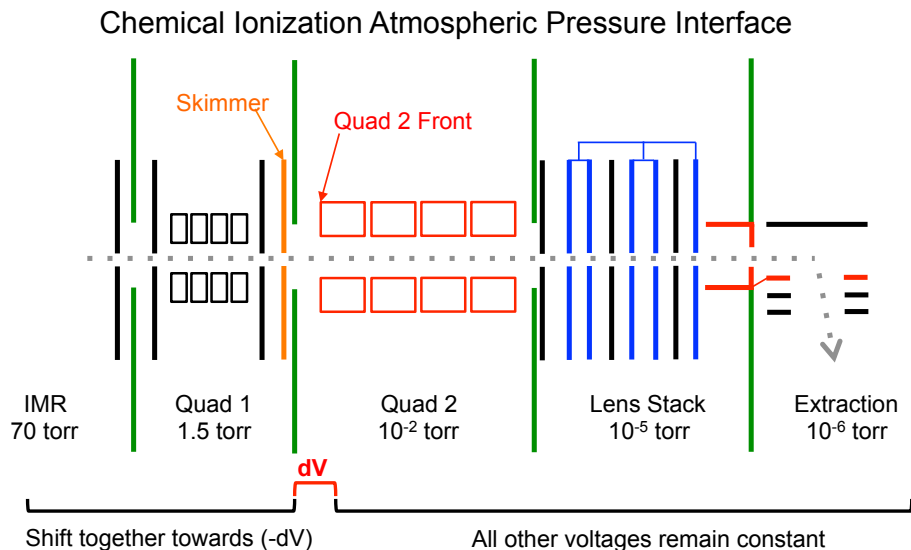
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**Figure 1.** An example collision-limited sensitivity determination of the ToF-CIMS. Top: the reagent ions and sum of total ions during the addition of high concentrations of  $^{15}\text{N}_2\text{O}_5$  to the inlet of the ToF-CIMS. By calibrating the output of our  $\text{N}_2\text{O}_5$  source independently (in this case by the UC, Berkeley TD-LiF instrument, Day et al., 2002), we are able to derive the collision-limited sensitivity of the instrument by adding the two detection channels as described in the text (Day et al., 2002; Huey et al., 1995). As total ion current (TIC) remains constant during the experiment despite the depletion of reagent ions  $\text{I}^- + \text{IH}_2\text{O}^-$  the mass transmission efficiency between 63 and 237 Th is therefore constant.

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**Figure 2.** A schematic of the voltages in the API region of the ToFwerk ToF-MS. The region of the mass spectrometer that we conduct declustering scanning is between the skimmer (orange) and the entrance to the second quadrupole (red). All voltages upstream of the skimmer are moved incrementally towards more negative voltages to create a stronger declustering field while keeping mass transmission effects constant by keeping the voltage gradients across each quadrupole constant, typically in steps of  $-1$  V. Iodide adducts which are formed in the ion molecule region (IMR) interact with the changing electric fields and dissociate based on their ion-molecule binding energy.

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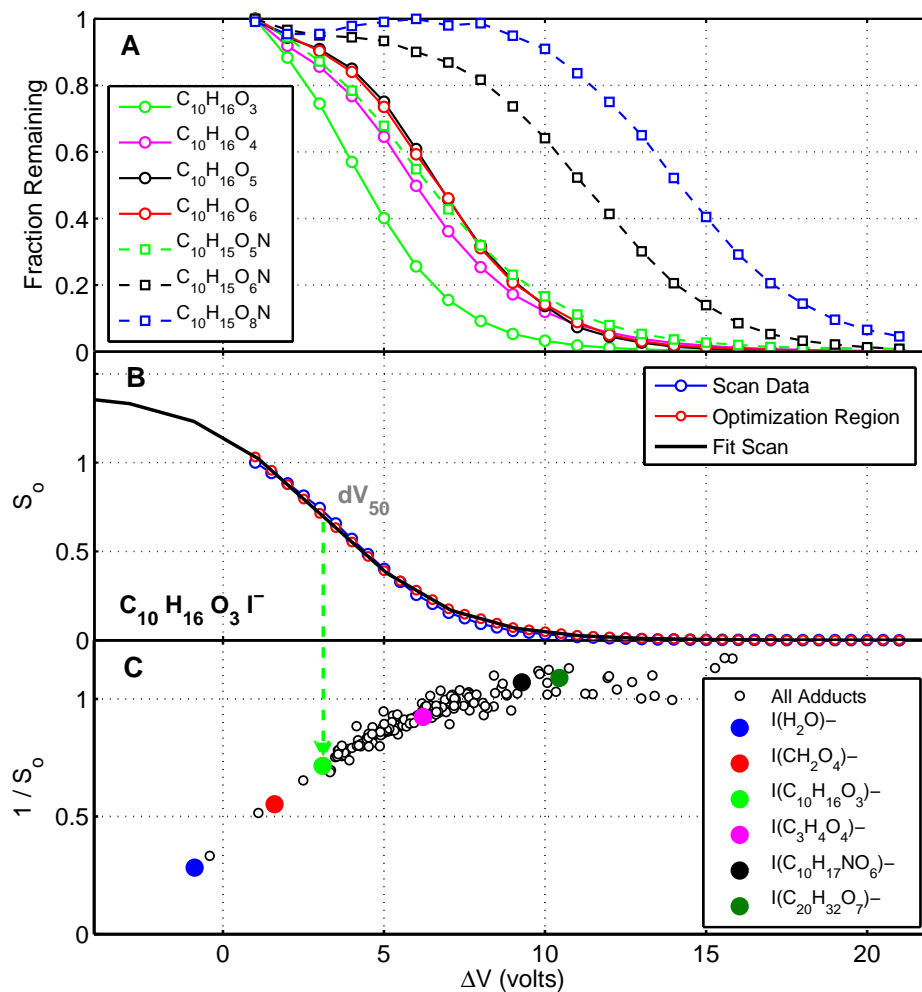
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**Figure 3.** Effective binding energy. Top: declustering scans of gas-phase products measured from the reaction of  $\alpha$ -pinene in the presence of ozone and  $\text{NO}_x$ . Some iodide adducts dissociate rapidly during the first few voltage steps. Multifunctional nitrates and highly oxidized  $\text{C}_{10}$  molecules show no dependence on the initial voltage steps before dissociating. We infer these compounds to be strongly bound to  $\text{I}^-$ , and therefore likely detected at a high sensitivity. Middle: an example of a non-linear least squares fit to the declustering scan is shown for  $\text{C}_{10}\text{H}_{16}\text{O}_3\text{I}^-$ . The raw scan data is shown in blue circles, the region of optimization for the fit is shown in red, and the extrapolated scan curve is shown in black, constraining  $S_o$ . Bottom: the results of fitting declustering scans ( $1/S_o$ ) shows a plateauing effect as a function of  $dV_{50}$ . We use  $dV_{50}$  as a measure of the relative binding energy between compounds. In colored dots, specific molecules are shown which span the binding enthalpy space.

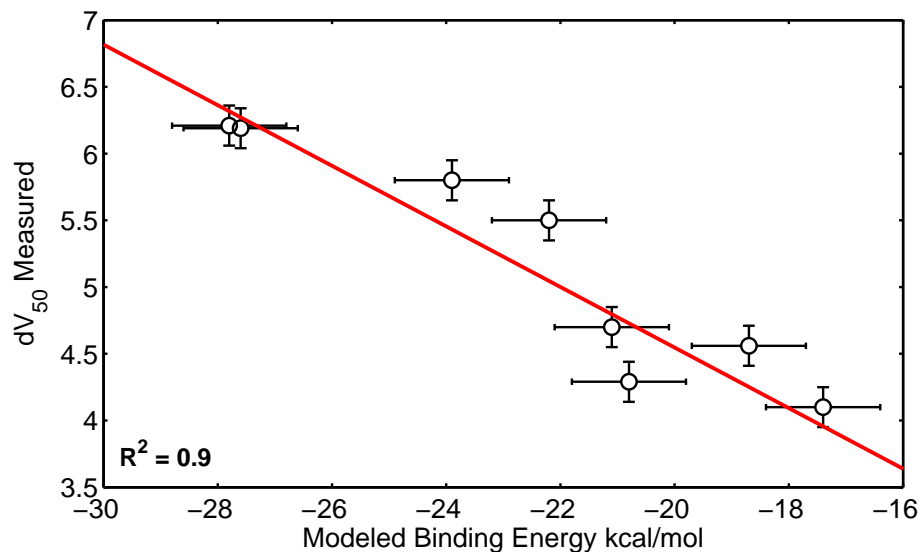
## Kinetic and thermodynamic constraints on I-CIMS sensitivity

F. D. Lopez-Hilfiker et al.

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**Figure 4.** The relationship between calculated binding enthalpy and  $dV_{50}$  is shown for compounds which were observed from the oxidation of  $\alpha$ -pinene in the presence of  $\text{NO}_x$  and for which quantum calculations have been performed (see Table 1). The modeled and measured relationship allows estimation of the binding energy of molecules which are too complex or computationally intensive to calculate. Also shown in red is a linear least squares fit to the data ( $R^2 = 0.9$ ).

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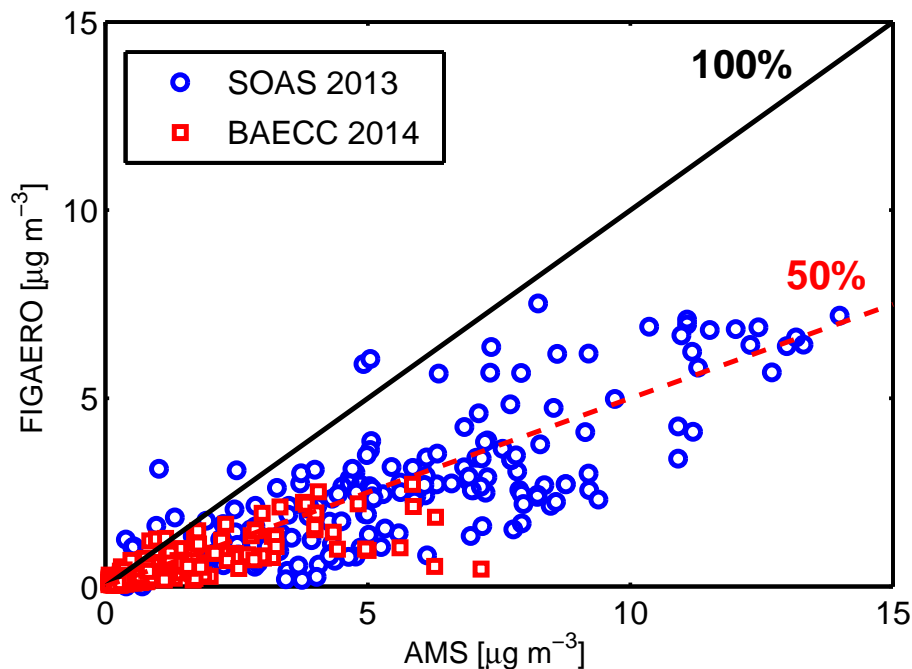
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**Figure 5.** Application of the collision limit to secondary organic aerosol concentration utilizing a FIGAERO inlet. The application of the collision limit allows conversion of detected signals to a lower limit mass loading, and despite this assumption, the mass loading explains a large fraction of SOA (~ 50 %) and is highly correlated with total organic aerosol mass concentrations measured by an AMS ( $R_{\text{SOAS}} = 0.82$  and  $R_{\text{BAEC}} = 0.76$ ). The lower correlation for BAEC is likely because of lower total organic and perhaps because the AMS was located on the ground, while the FIGAERO was located at the top of a 35 m tower. To attempt to reduce this potential bias, only data points during daytime are plotted for BAEC as surface inversions (below the tower) were regularly observed at night.

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