TAbMEP Assessment: ICARTT CO Measurements

1. Introduction

Here we provide the assessment for the carbon monoxide (CO) measurements taken from multiple aircraft platforms during the summer 2004 ICARTT field campaign [*Fehsenfeld et al.*, 2006, *Singh et al*., 2006]. This assessment is based upon the five wing-tip-to-wing-tip intercomparison flights conducted during the field campaign, plus a comparison between the two NASA DC-8 instruments on all ICARTT research flights. Recommendations provided here offer TAbMEP assessed uncertainties for each of the measurements and a systematic approach to unifying the ICARTT CO data for any integrated analysis. These recommendations are directly derived from the instrument performance demonstrated during the ICARTT measurement comparison exercises and are not to be extrapolated beyond this campaign.

2. ICARTT CO Measurements

Six different CO measurement techniques were deployed on four aircraft. Table 1 summarizes these techniques and gives references for more information. Most of the CO measurements were conducted under dry conditions, i.e., the reported values are dry air mixing ratio. Two instruments measured CO at ambient conditions (marked by an "*" in Table 1). The difference, in general, between measurements made under ambient conditions and those made in a dried sample is a small but quantifiable function of the ambient humidity and is largest in the boundary layer where water is most abundant. Since the sampling humidity was not measured or reported by any of the instruments in this study, it is not possible for the panel to make a precise assessment of this difference. Based on the intercomparison between NASA DC-8 and NOAA WP-3D, the maximum difference is estimated to be less than 2.5%. For all intercomparisons considered here, the differences between measurements made under ambient and dry conditions are small and not easily distinguishable from other instrumental differences. As a general policy, the panel does not change PI reported data, however, a user of the data may wish to undertake the conversion for a particular analysis.

Table 1. CO measurements deployed on aircraft during ICARTT

Aircraft	Instrument	Reference
NASA DC-8	DACOM (Differential Absorption CO Measurement)	*Warner et al.* [2007]
NASA DC-8	WAS (Whole Air Sampler)	*Barletta et al.* [2002]
NOAA WP-3D	VUVF (Vacuum UV fluorescence)*	*Holloway et al.* [2000]
FAAM BAe-146	VUVF (Vacuum UV fluorescence)	*Gerbig et al.* [1999]
DLR Falcon	VUVF (Vacuum UV fluorescence)	*Gerbig et al.* [1999]
DLR Falcon	TDLAS (Tunable Diode Laser Absorption Spectroscopy)*	*Wienhold et al.* [1998] and *Fischer et al.* [2002]

*Measurement made at ambient humidity.

3. Summary of Results

Table 2 summarizes the assessed 2σ precisions, biases, and uncertainties. More detailed descriptions are provided to illustrate the process for assessment of bias and precision in Sections 4.1 and 4.2 respectively. The assessed 2σ precisions reported in Table 2 are equal to twice the highest adjusted precision value for that instrument listed in Table 4. Table 2 also reports an assessed bias (see Section 4.1 for details) that can be applied to maximize the consistency between the data sets. The assessed bias should be subtracted from the reported data to 'unify' the data sets. The assessed bias is derived from intercomparison periods only and may be extrapolated to the entire mission if one assumes instrument performance remained constant throughout the mission. For one CO instrument (Falcon VUVF), the assessed bias is smaller than the uncertainty reported by the PI, so no bias adjustment need be made when combining this data set. The bias estimate for the Falcon TDLAS instrument (Table 3) is strongly influenced by a short period of the intercomparison flight when large differences were noted (see Figs. 5 and A5). If these apparent outliers were excluded, then the estimated adjustment would be significantly smaller. Consequently, we provide no assessed bias or 2σ uncertainty for this instrument as a robust statistical assessment cannot be performed. The interested researcher is encouraged to contact the PI before using the Falcon TDLAS data. The recommended 2σ uncertainty in Table 2 is the larger of either the uncertainty reported by the PI or the quadrature-sum of the assessed 2σ precision and assessed bias listed in Table 2.

Table 2. Recommended ICARTT CO measurement treatment

Aircraft/ Instrument	Reported 2σ Uncertainty	Assessed 2σ Precision	Assessed Bias	Recommended 2σ Uncertainty
NASA DC-8 DACOM	2% or 2 ppbv	2.4%	$2.84 – 0.020\ CO_{DACOM}$	Quadrature Sum
NASA DC-8 WAS	5%	11%	$-0.04 + 0.011\ CO_{WAS}$	Quadrature Sum
NOAA WP-3D VUVF	5%	4.0%	$-3.18 + 0.023\ CO_{WP3D}$	Quadrature Sum
FAAM BAe-146 VUVF	None	2.8%	$-7.43 + 0.004\ CO_{BAe}$	Quadrature Sum
DLR Falcon VUVF	5%	5.0%	$0.52 – 0.015\ CO_{VUVF}$	Quadrature Sum
DLR Falcon TDLAS	5%	5.4%	See footnote [a]	See footnote [a]

[a]Not included since robust statistical assessment cannot be performed.

Figures 1a-1c display the precisions, biases, and recommended uncertainties for five of the six CO instruments. TDLAS on the Falcon is not included since we do not recommend a bias or 2σ uncertainty in Table 2. For four of the five instruments shown (DACOM, WAS, WP-3D VUVF and Falcon VUVF), the uncertainty is driven by the precision.

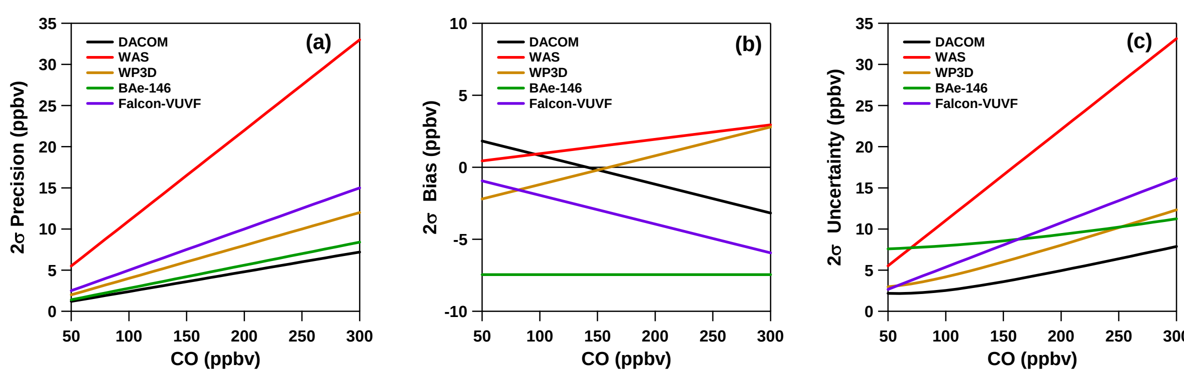

Figure 1. 2σ precision (panel a), 2σ bias (panel b), and 2σ uncertainty (panel c) for DACOM (black), WAS (red), WP-3D (gold), BAe-146 (green), and Falcon VUVF (purple) as a function of CO level. Values were calculated based upon data shown in Table 2.

4. Results and Discussion

4.1 Bias Analysis

Section 3.3 in the introduction describes the process used to determine the best estimate bias. Figure 2 shows the correlation and time series plots for each of the three WP-3D vs. DC-8 DACOM comparisons. The linear relationships listed in Table 3 were derived from the regression equations found in Figures 3 through 6. In the case of CO, there is little bias between four of the instruments (DACOM, WAS, WP-3D VUVF and Falcon VUVF), a relatively large negative bias in the BAe-146 VUVF data (see Figures 7-11), and a moderate bias in the Falcon TDLAS instrument. The Falcon bias is exaggerated by a period of large bias indicated by the vertical line of points in Figure 11. For these reasons, the BAe-146 VUVF and the Falcon TDLAS regressions are not included in the calculation of the reference standard for comparison (RSC), as defined in the introduction. The resulting RSC can be expressed as a function of the DACOM CO measurement as the following:

$$RSC_{CO} = -2.84 + 1.020 CO_{DACOM}$$

The RSC is then used to calculate the best estimate bias as described in Section 3.3 of the introduction. It should be noted that the initial choice of the reference instrument (DACOM) is arbitrary, and has no impact on the final recommendations. Table 3 summarizes the assessed measurement bias for each of the six ICARTT CO measurements. Note that additional decimal places were carried in the calculations to ensure better than 0.1 ppbv precision.

Table 3. ICARTT CO bias estimates

Aircraft/ Instrument	Linear Relationships[a]	Best Estimate Bias (a + b CO) (ppbv)
NASA DC-8 DACOM	$CO_{DACOM} = 0.00 + 1.000\ CO_{DACOM}$	$2.84 – 0.020\ CO_{DACOM}$
NASA DC-8 WAS	$CO_{WAS} = -2.91 + 1.031\ CO_{DACOM}$	$-0.04 + 0.011\ CO_{WAS}$
NOAA WP-3D VUVF	$CO_{WP3D} = -6.17 + 1.044\ CO_{DACOM}$	$-3.18 + 0.023\ CO_{WP3D}$
FAAM BAe-146 VUVF	$CO_{BAe\text{-}146} = -10.30 + 1.024\ CO_{DACOM}$ [b]	$-7.43 + 0.004\ CO_{BAe}$
DLR Falcon VUVF	$CO_{DLR\text{-}VUVF} = -2.28 + 1.006\ CO_{DACOM}$	$0.52 – 0.015\ CO_{VUVF}$
DLR Falcon TDLAS	$CO_{DLR\text{-}TDLAS} = -0.66 + 1.028\ CO_{DACOM}$ [b]	$2.18 + 0.008\ CO_{TDLAS}$

[a]Derived from Figs. A2-A5.
[b]Not included in RSC derivation, see text for details.

4.2 Precision Analysis

A detailed description of the precision assessment is given in Section 3.1 of the introduction. The IEIP precision, expected variability, observed variability, and the adjusted precision are summarized in Table 4. Based on the results presented in Table 4, the largest "adjusted precision" value is taken as a conservative precision estimate for each ICARTT CO instrument and twice that value is listed in Table 2 as the assessed 2σ precision.

Table 4. ICARTT CO precision (1σ) comparisons

Flight	Platform/ Instrument	IEIP Precision	Expected Variability	Observed Variability	Adjusted Precision
07/22	DC-8 DACOM	0.9%	1.5%	2.0%	1.2%
	WP-3D VUVF	1.2%			1.6%
07/31	DC-8 DACOM	0.8%	1.7%	1.6%	0.8%
	WP-3D VUVF	1.5%			1.5%
08/07	DC-8 DACOM	0.6%	1.5%	2.1%	0.9%
	WP-3D VUVF	1.4%			2.0%
07/28	DC-8 WAS	5.5%[a]	5.5%	4.2%	5.5%
	BAe-146 VUVF	0.5%			0.5%
08/03	BAe-146 VUVF	0.5%	1.0%	2.8%	1.4%
	Falcon VUVF	0.9%			2.5%
08/03	BAe-146 VUVF	0.5%	1.3%	2.8%	1.1%
	Falcon TDLAS	1.3%			2.7%

[a]estimated from DC-8 WAS and DC-8 DACOM comparison, see Fig. 10.

The DC-8 WAS technique provides only intermittent results with an integration time of about 1 minute. The IEIP procedures are not applicable in this case. As noted in Table 4, the DC-8 WAS precision is estimated from the standard deviation of the relative difference, i.e., [CO(DC-8 WAS) - CO(DC-8 DACOM)]/ CO(DC-8 DACOM) plotted in Figure 16, which is based on all available overlapping data from the entire ICARTT campaign period. It should also be recognized that the DC-8 WAS precision required the use of, but was not sensitive to the DC-8 DACOM IEIP analysis (see Figure 16).

To minimize the effect of bias, we make corrections for bias before computing the observed variability, as the bias may have a significant impact on the observed variability. Figures 7 – 11 show the magnitude of the bias for each intercomparison. The assessed values of the observed variability are displayed in Figure 12 – 16. The final analysis results are shown in Table 2. Over 90% of the data falls within the combined recommended uncertainties for each intercomparison, which is consistent with the TAbMEP guideline for unified data sets.

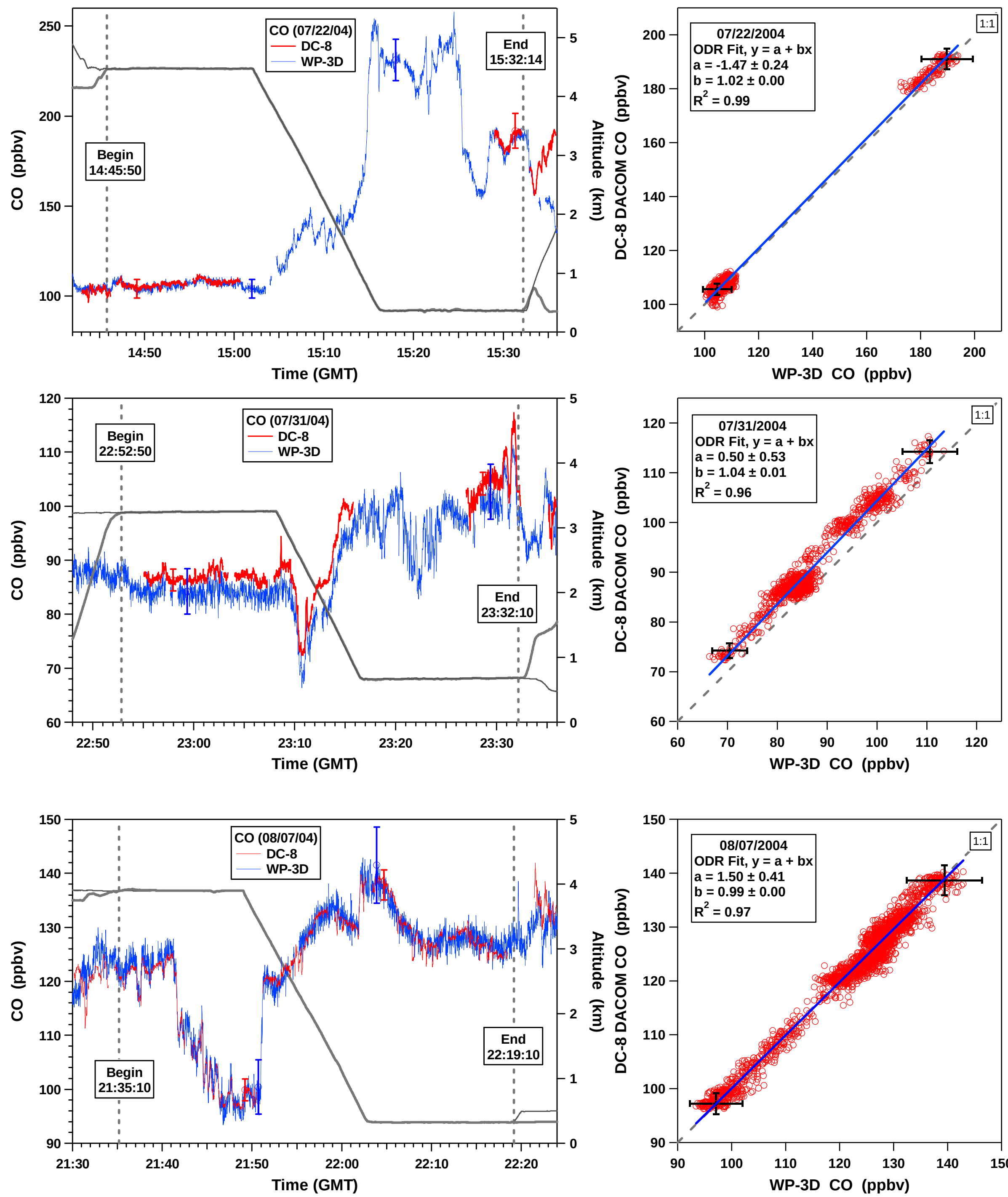

Figure 2. (left panels) Time series of CO measurements and aircraft altitudes from two aircraft on the three intercomparison flights between the NASA DC-8 (DACOM) and the NOAA WP-3D. (right panels) Correlations between the CO measurements on the two aircraft. Error bars shown depict the reported measurement uncertainties.

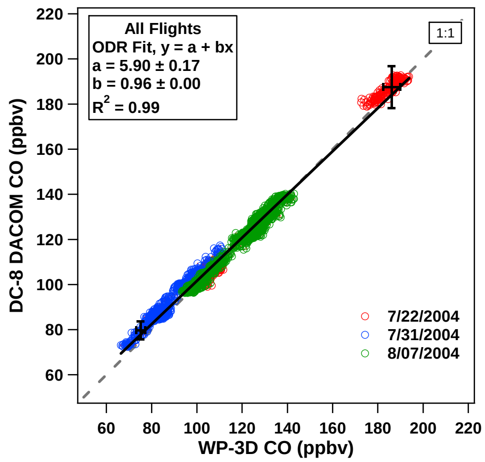

Figure 3. Combined correlation for the CO measurements on NASA DC-8 and the NOAA WP-3D for 7/22, 7/31, and 8/7 2004. Error bars shown depict the reported measurement uncertainties.

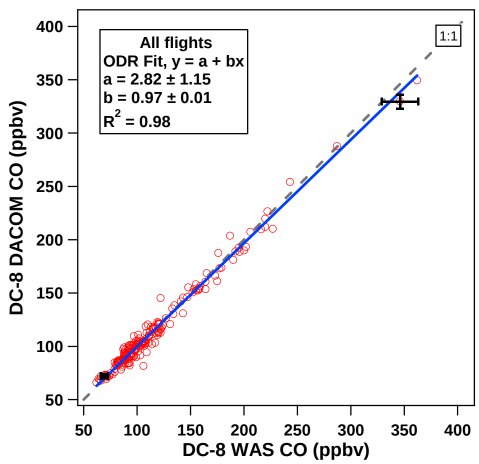

Figure 4. Correlation for the CO measurements (DACOM and WAS) on NASA DC-8 for all available data. Error bars shown depict the reported measurement uncertainties.

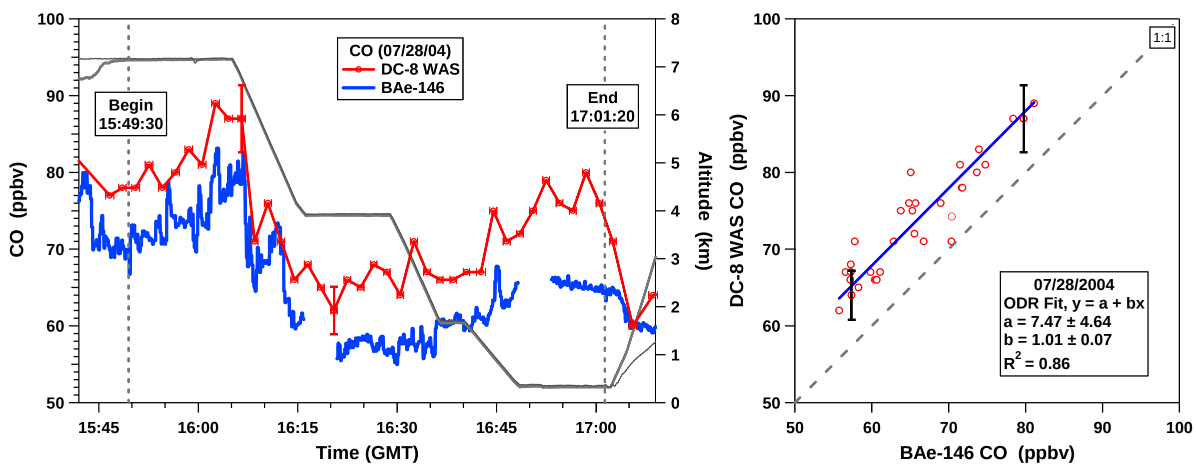

Figure 5. (left panel) Time series of CO measurements and aircraft altitudes from the intercomparison flight between the NASA DC-8 and the FAAM BAe-146. (right panel) Correlations between the CO measurements on the two aircraft. Error bars shown depict the reported measurement uncertainties.

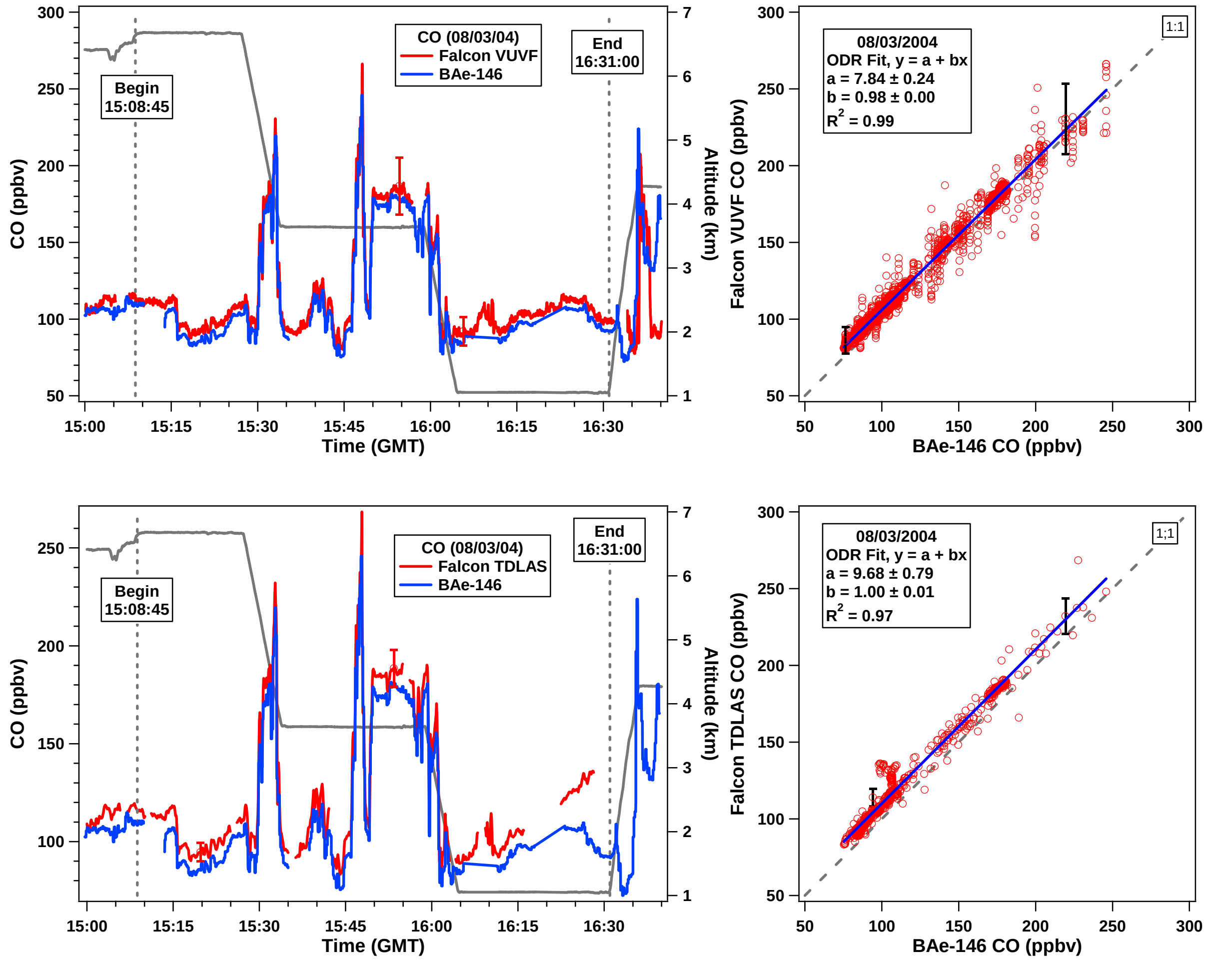

Figure 6. (left panel) Time series of CO measurements and aircraft altitudes from the intercomparison flight between the FAAM BAe-146 and the DLR Falcon. (right panel) Correlations between the CO measurements on the two aircraft. Error bars shown depict the reported measurement uncertainties.

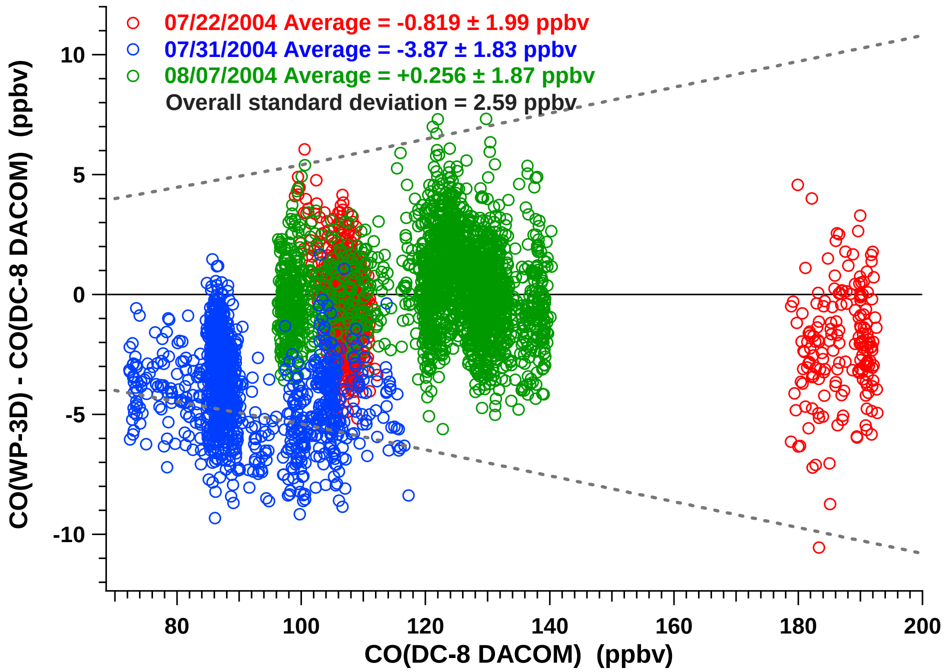

Figure 7. Difference between CO measurements from the three DC-8/WP-3D intercomparison flights as a function of the DC-8 DACOM CO. The dashed lines indicate the range of the results expected from the reported 2σ measurement uncertainties.

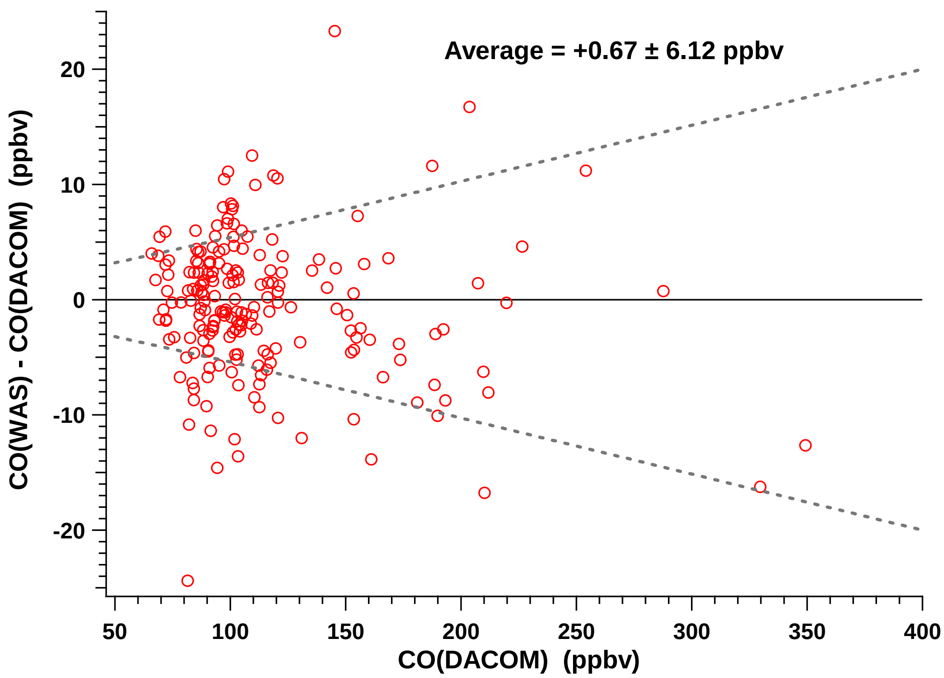

Figure 8. Difference between CO measurements from all ICARTT flights of the DC-8 as a function of the DC-8 DACOM CO. The dashed lines indicate the range of the results expected from the reported measurement uncertainties.

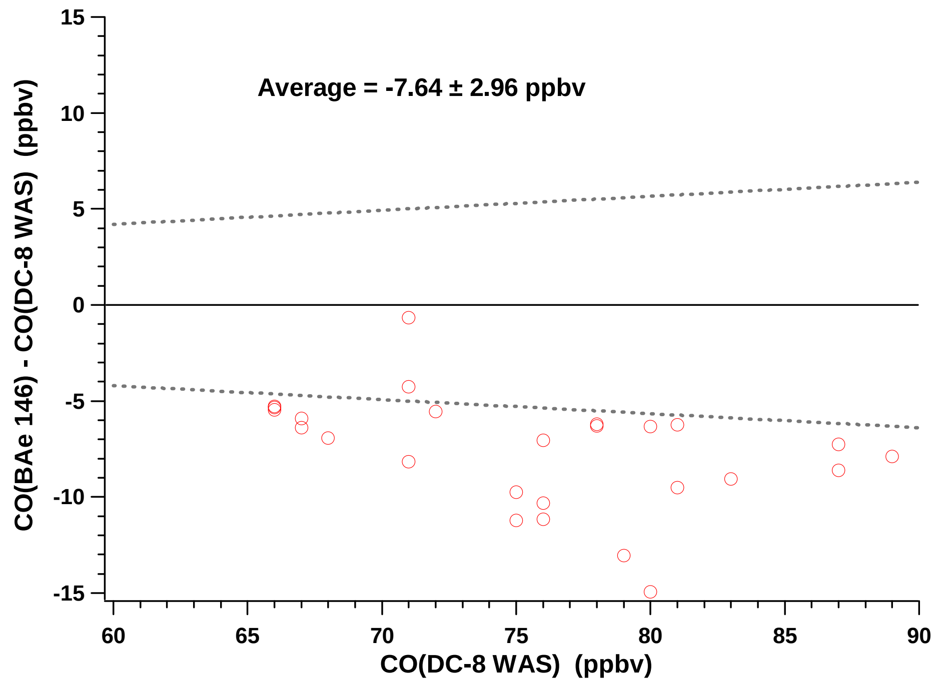

Figure 9. Difference between CO measurements from the DC-8/BAe-146 intercomparison flight (07/28) as a function of the DC-8 WAS CO. The dashed lines indicate the range of the results expected from the reported 2σ measurement uncertainties.

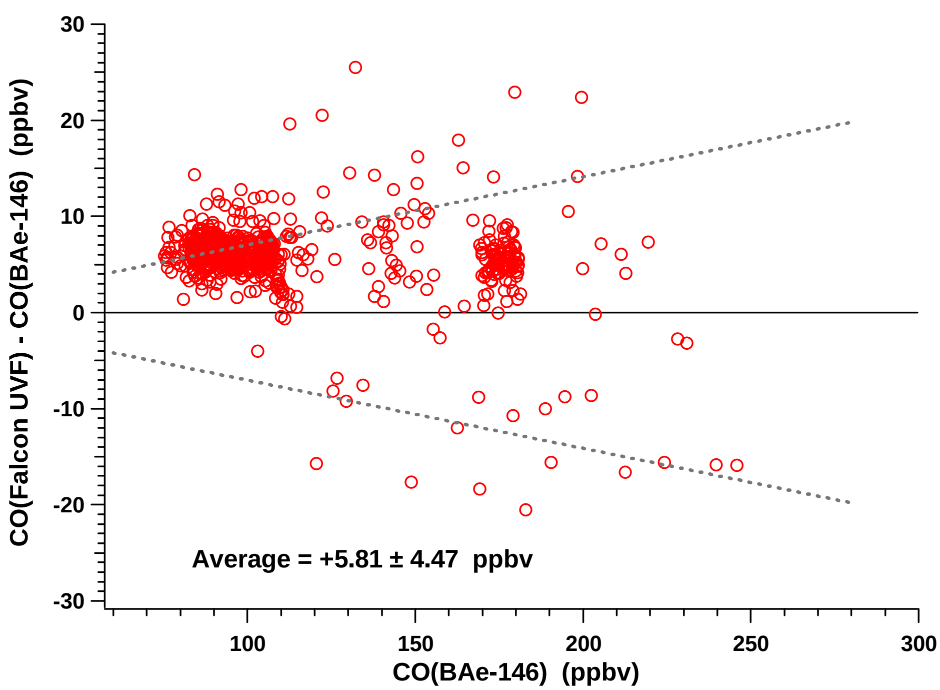

Figure 10. Difference between CO measurements from the BAe-146/DLR Falcon (VUVF) intercomparison flight (08/03) as a function of the BAe-146 VUVF CO. The dashed lines indicate the range of the results expected from the reported 2σ measurement uncertainties.

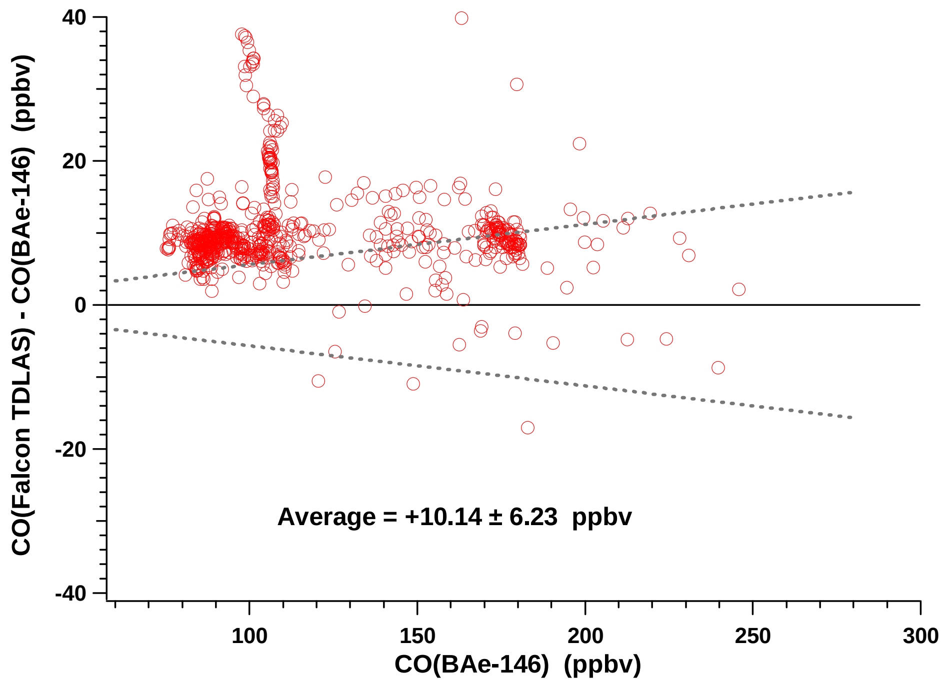

Figure 11. Difference between CO measurements reported from the BAe-146/DLR Falcon (TDLAS) intercomparison flight (08/03) as a function of the BAe-146 VUVF CO. The dashed lines indicate the range of the results expected from the reported 2σ measurement uncertainties.

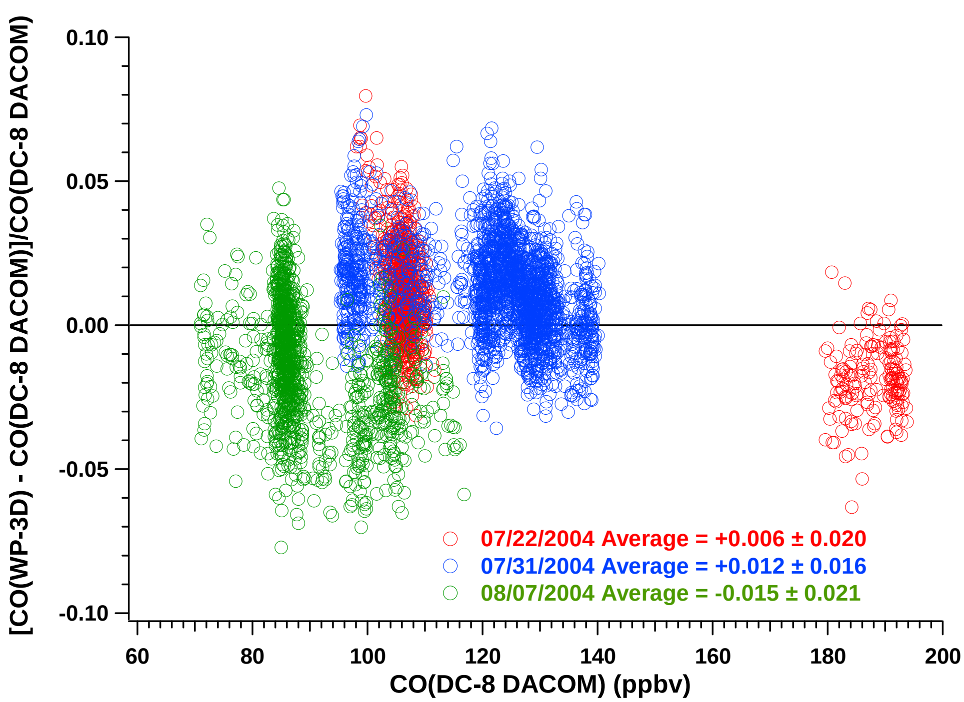

Figure 12. Relative difference between CO measurements from the three DC-8/WP-3D intercomparison flights as a function of the DC-8 DACOM CO. A correction was made to account for bias.

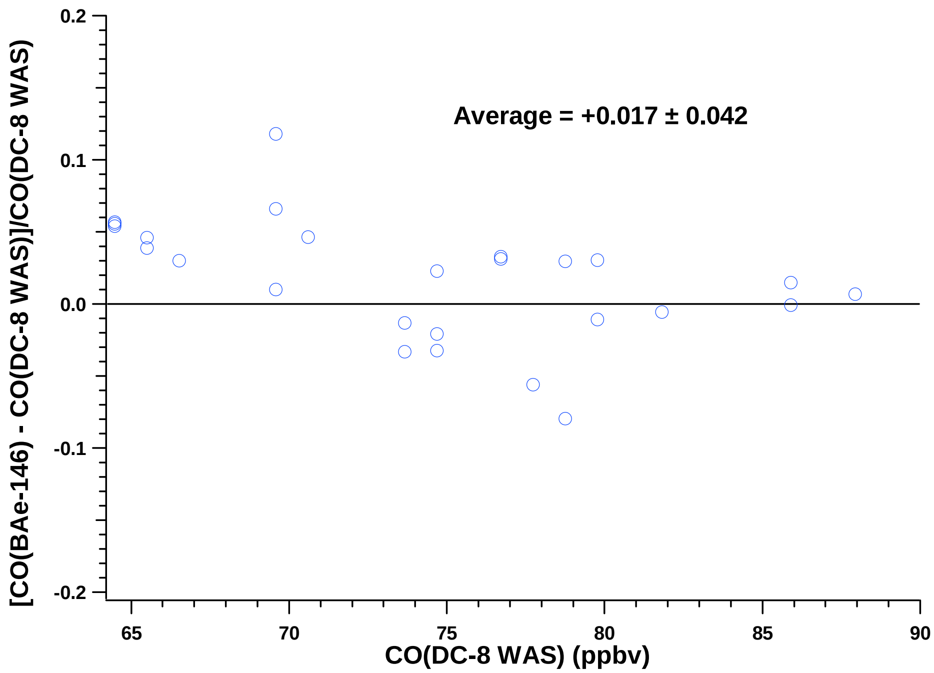

Figure 13. Relative difference between CO measurements from the DC-8/BAe-146 intercomparison flight (07/28) as a function of the DC-8 WAS CO. A correction was made to account for bias.

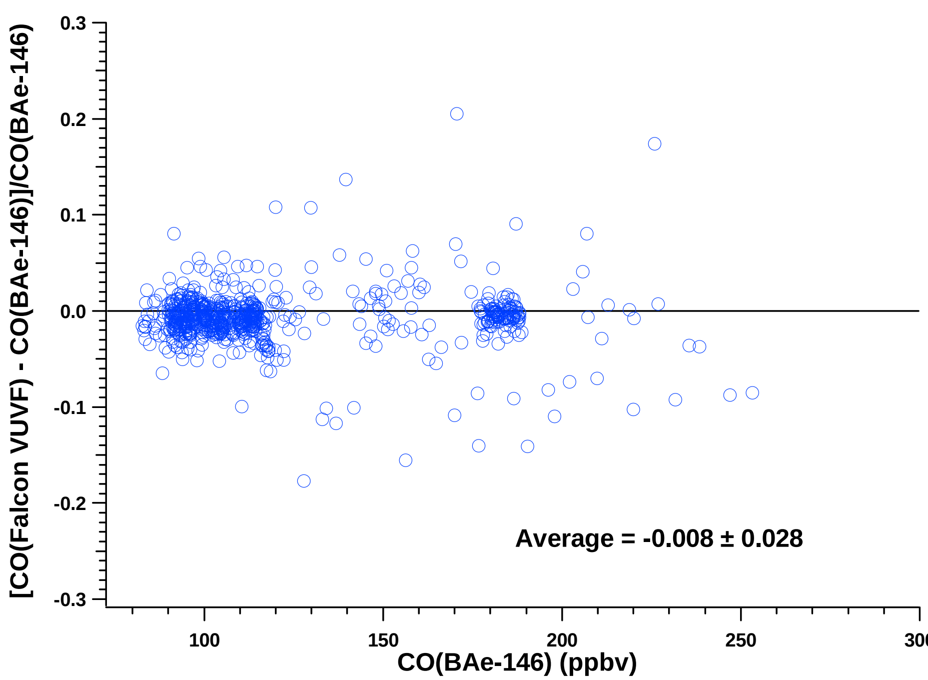

Figure 14. Relative difference between CO measurements reported from two instruments during the BAe-146/DLR Falcon (VUVF) intercomparison flight (08/03) as a function of BAe-146 VUVF CO. A correction was made to account for bias.

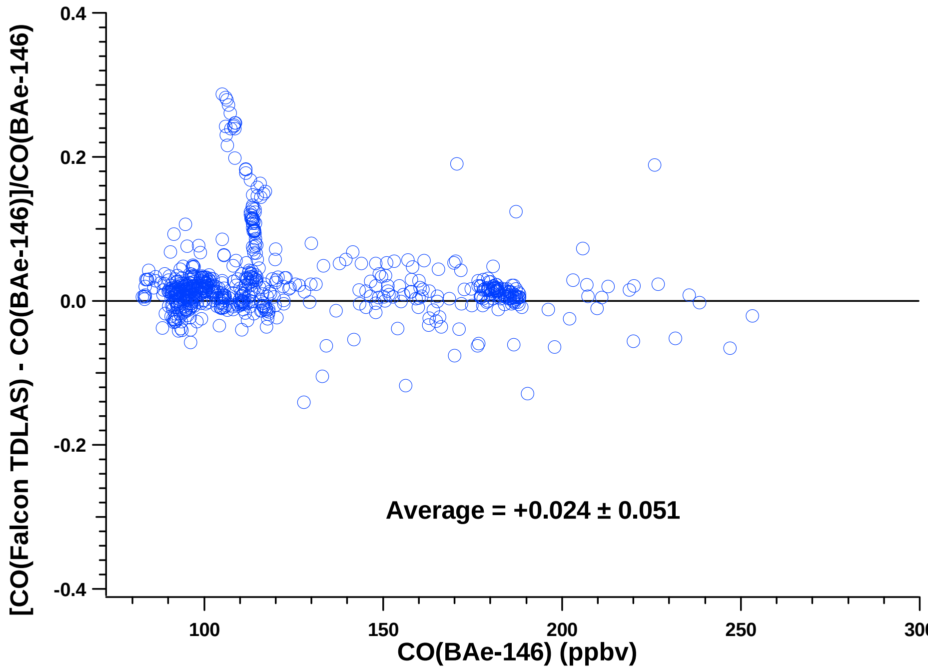

Figure 15. Relative difference between CO measurements from the BAe-146/DLR Falcon (TDLAS) intercomparison flight (08/03) as a function of the BAe-146 VUVF CO. A correction was made to account for bias.

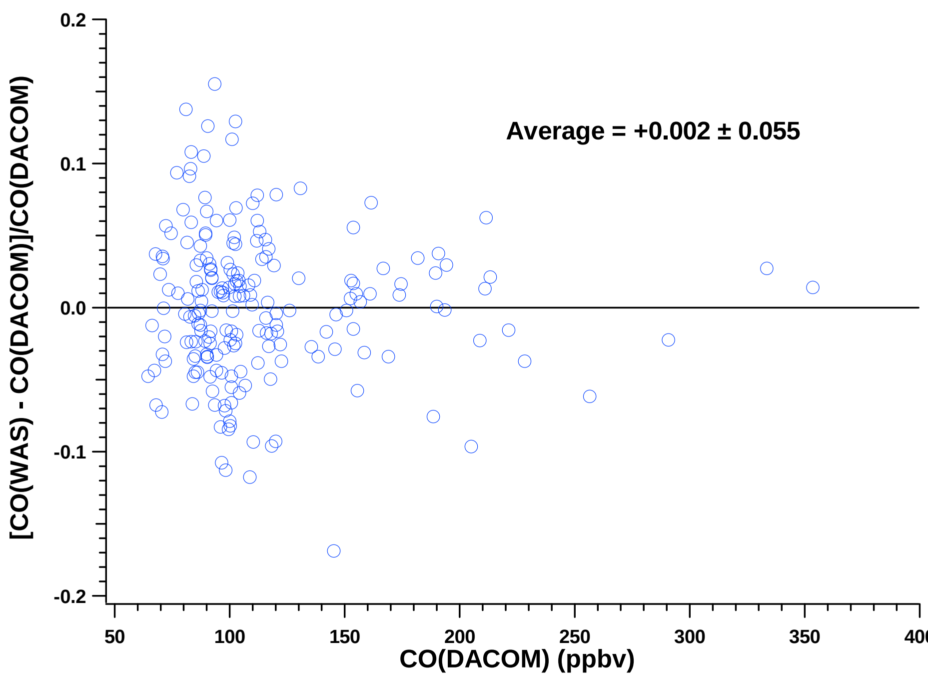

Figure 16. Relative difference between CO measurements reported from all ICARTT flights of the DC-8 as a function of the DC-8 DACOM CO. A correction was made to account for bias.

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