Analysis of Biases in XCO_2 measured by a pulsed multiwavelength airborne lidar during the 2017 ASCENDS/ABoVE Campaign

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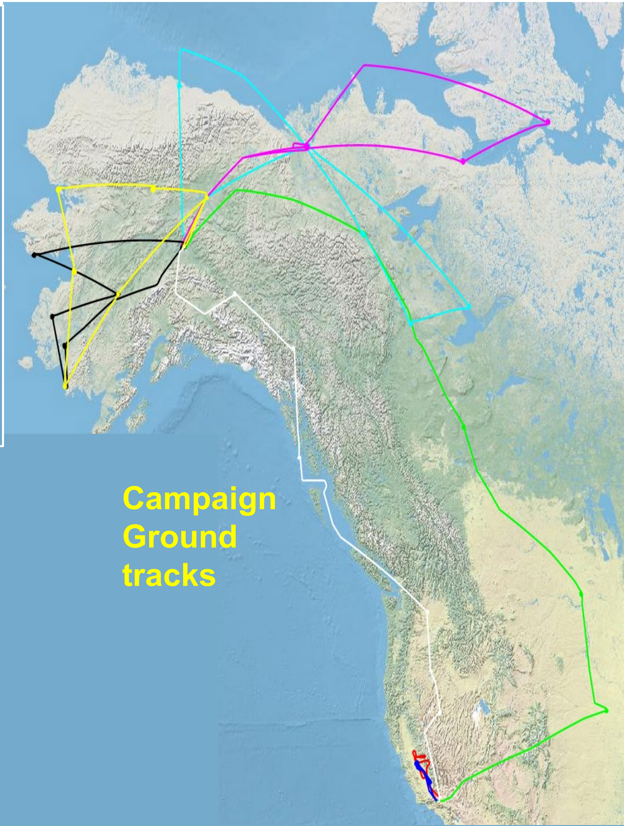
Campaign flown on NASA DC-8, carrying:

- Goddard CO_2 Sounder Lidar
- Goddard Picarro, *in situ*
- LaRC AVOCET, *in situ*
- LaRC DLH , *in situ*

- 8 flights
- July 20- Aug 8, 2017
- 55 hours of airborne measurements
- Comparison with *in situ* at 47 locations



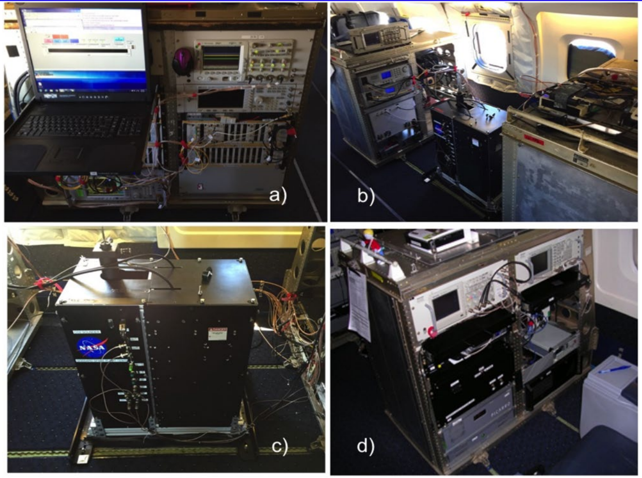
Campaign Ground tracks

Introduction

- Pulsed IPDA lidar measurements of XCO_2 over long flight lines
- Lidar measurements of XCO_2 in Arctic, for first time
- Measurements made in diverse set of atmospheric & surface conditions
- Analysis of XCO_2 measurements showed:
  - Gradients in XCO_2: North-south, East-west & Locally
  - Local features in XCO_2, including one caused by wildfires
  - Vertically resolved aerosol scattering profiles

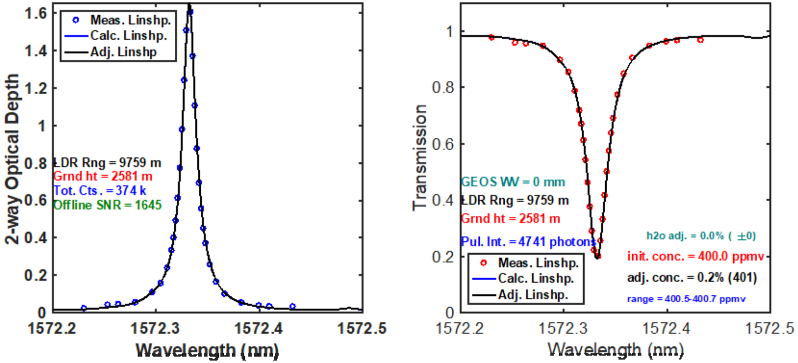
Spiral-down maneuvers allowed assessment of measurement "bias"

CO_2 Sounder Lidar & other campaign instruments



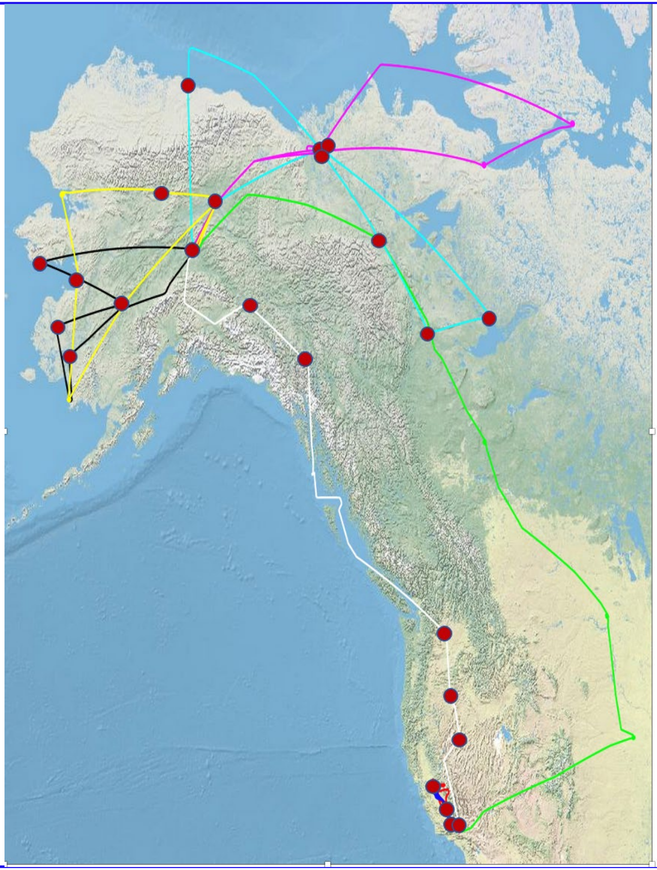
Other science instruments on 2017 campaign

- **Picarro** (Randy Kawa) – in situ CO2 and WV
- **AVOCET** (Josh DiGangi/LaRC) – in situ CO2, CH4, CO
- **DLH** (Glenn Diskin/LaRC) – in situ WV
- **ACES** (Mike Obland/LaRC) – IPDA lidar to measure XCO2 using line near 1571 nm. Uses modulated CW lasers at 3 wavelengths



- Direct Detection IPDA lidar - emits 10 kHz train of laser pulses
- Measures column CO_2 absorption using 1572.33 nm line.
- Laser pulses - stepped in 30 wavelengths across line; ~300 scans/sec
- Time resolved receiver, HgCdTe APD detector
- Measures backscatter profile, range & samples of CO_2 line shape
- XCO_2 Retrievals (Sun et al, AMT 2021):
  - Line shape samples, range to scattering surface
  - Atmospheric state (DC-8 measurements or GEOS-5)
  - CO_2 Spectroscopy: HITRAN 2008, Lamouroux 2010 line mixing

2017 ASCENDS Airborne Campaign 37 Spiral locations selected for comparison of Lidar XCO2 vs in situ XCO2



Bias =
Lidar – in situ in upper 2 km of each spiral

For each spiral, used 3 different approaches to correct for lidar receiver's spectral non-uniformity:

- Linear
- Nonlinear (quadratic)
- Shifted BPF

Notation for each spiral:

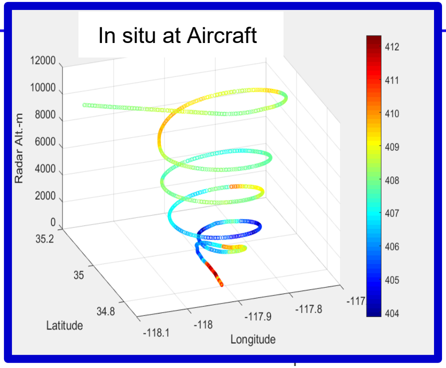
- **Bold – lowest bias**
- Red: highest bias

2022 Spiral Analysis (Lidar-Avocet)

Flight MonthDay	Spiral	Spiral #	Ave of top 2 1-km alts: Ave Alt Linear	Ave Alt Nonlinear	Ave alt BPF shifted 30 pm
720	Cas1	1			
720	Cas2	2			
720	Edw	3	0.89	0.19	0.55
		4			
721	Cas1	5	0.85	0.19	0.35
721	Port1	6	1.01	-0.08	0.54
721	cas2	7			
721	Port2	8			
721	Cas3	9			
		10			
727	GrandIsland	11			
727	Minott	12			
727	LoonRiv	13			
		14			
731	Inuvl	15	0.83	0.01	0.12
731	NormW	16	1.83	0.38	1.42
731	FortSimp	17	0.52	0.07	0.05
731	Yellowk	18	1.25	0.33	0.82
731	Inuvik2	19	0.26	-0.54	-0.18
731	Deadhor	20	0.48	-0.26	0.01
		21			
802	Inuvik1	22	0.85	0.05	0.12
802	Kugluktuk	23			
802	CambridgeB	24			
802	Inuvik2	25			
		26			
805	Bethel	27	0.68	-0.10	0.20
805	Nome	28	0.45	-0.85	0.01
805	St Marys	29	-0.22	-1.13	-0.65
805	McGrath	30	0.85	-0.21	0.36
805	Fairbanks	31	0.20	-0.73	-0.24
		32			
806	Bettles	33	1.60	0.29	1.13
806	Kotzebe	34			
806	Unalakleet	35	0.85	-0.23	0.44
806	McGrath	36			
806	FortYuk	37	0.33	-0.51	-0.11
		38			
808	Northway	39	1.29	0.37	0.84
808	WhiteHorse	40	1.30	0.49	0.84
808	MosesLake	41	0.07	-0.88	-0.36
808	Wildhorse	42	1.37	0.12	0.88
808	Winnemucca	43	0.90	-0.28	0.35
808	Edwards	44	0.30	-0.28	-0.10
For campaign	Count		Mean diff for campaign	Mean diff for campaign	Mean diff for campaign
# of spirals	37		0.78	-0.15	0.31
			Std Dev of Means	Std Dev of Means	Std Dev of Means
			0.50	0.44	0.50

Sample Airborne Measurements made in 2017

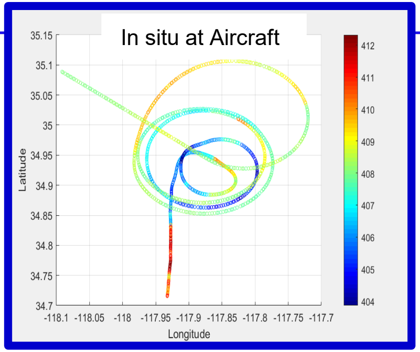
July 20 Spiral over Edwards CA: CO_2 & XCO_2 Retrievals



Picarro (in situ) CO2 measurements at aircraft made during spiral

<- Side view

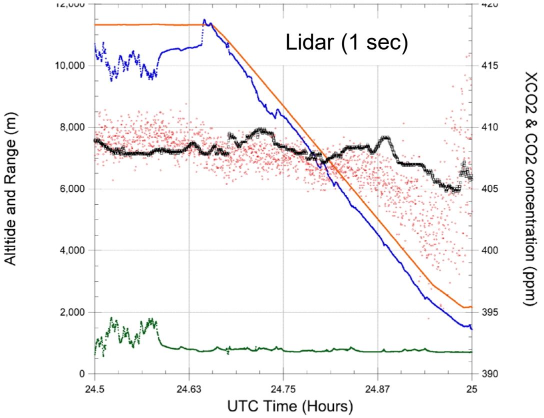
Top view->



Red dots: XCO2 from CO2 Sounder Lidar

Black dots: CO2 (at altitude) from in situ

All XCO2 Retrievals use 1 second averaging time

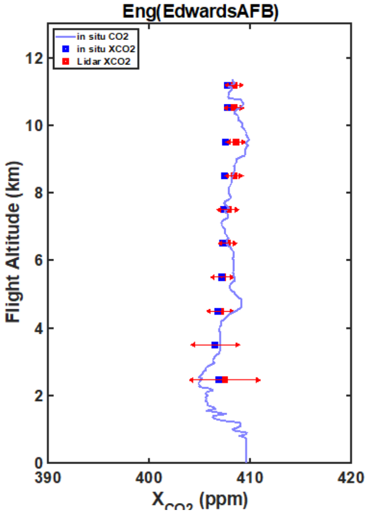


Comparison of XCO2 measurements:

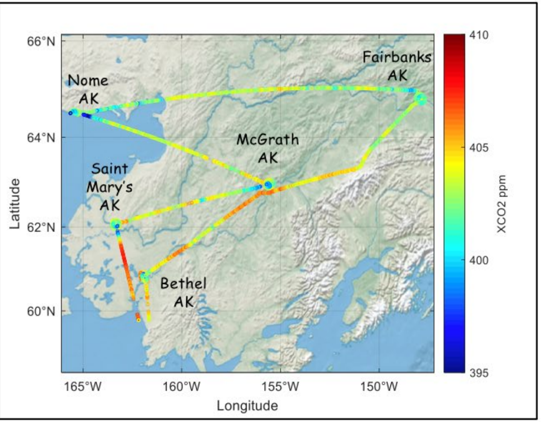
- *Red – lidar*
- *Blue dots - In situ, ave'd to surface*

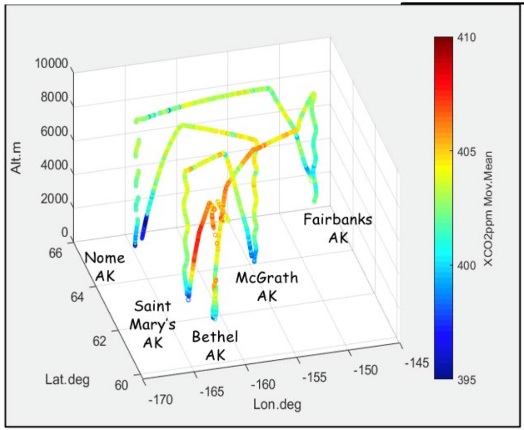
Reference atmosphere (LUT) for XCO2 retrievals based on:
DC-8 T & P
PICARRO **WV**

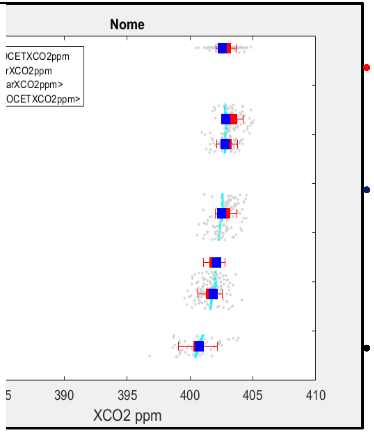
Lidar retrievals use 1 second averaging time



Lidar XCO_2 vs *in situ* XCO_2 in Spirals
(for Aug 5, 2017 flight in Alaska)







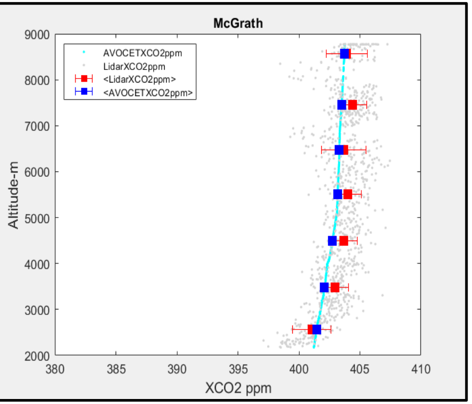
Where:

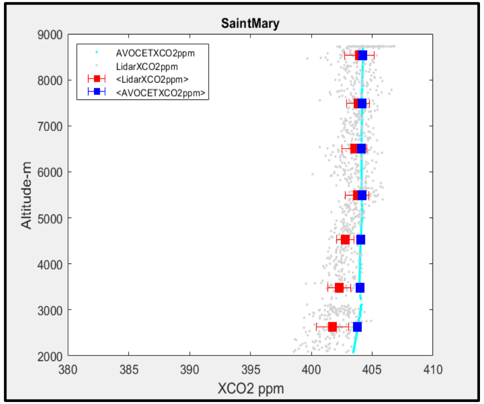
- **Red:** Lidar 1-sec retrievals in 1 km vertical bins

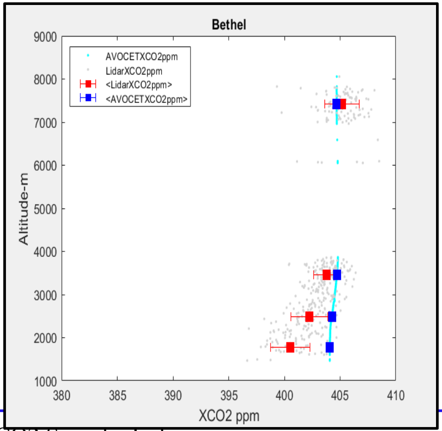
  (mean +/- 1 std dev)
- **Blue dots** – Column XCO_2 from AVOCET using lidar vertical weighting function

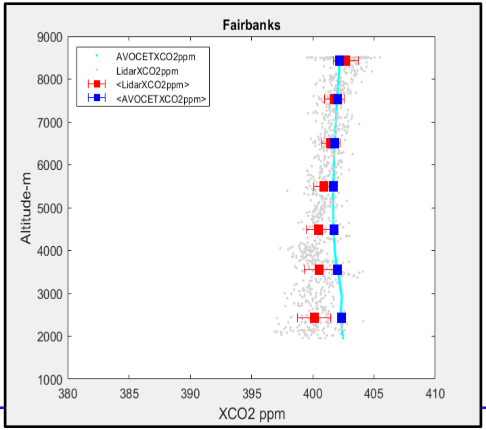
For this flight:

- **< 0.5 ppm difference between Lidar & *in situ* XCO_2 at altitudes >4 km**

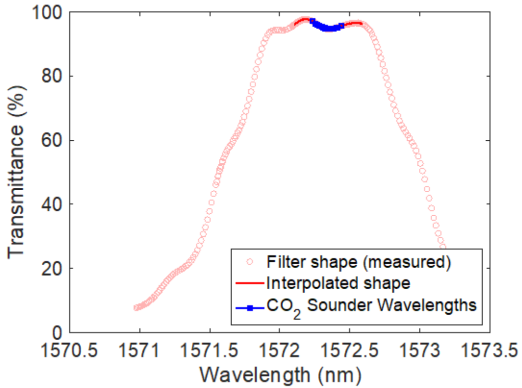








Lidar receiver has spectral bandpass filter to reject sunlight



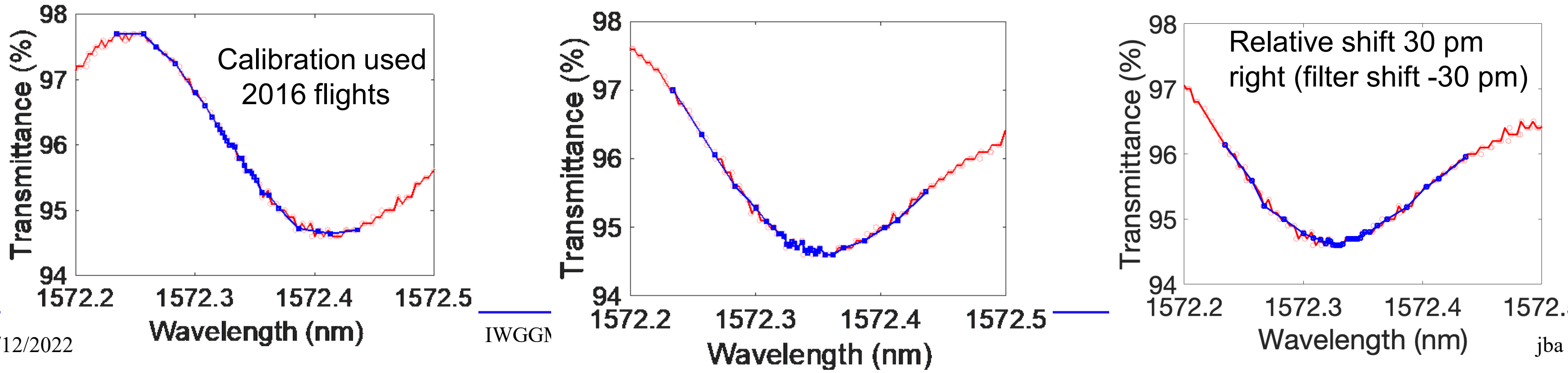
- An ideal filter has exactly same transmission at all laser wavelengths
- Ours used in 2017 had a few % variability
- This slightly distorted the lidar measured CO_2 line shape & caused bias in retrieval

Our present Line fitting Retrieval allows either:

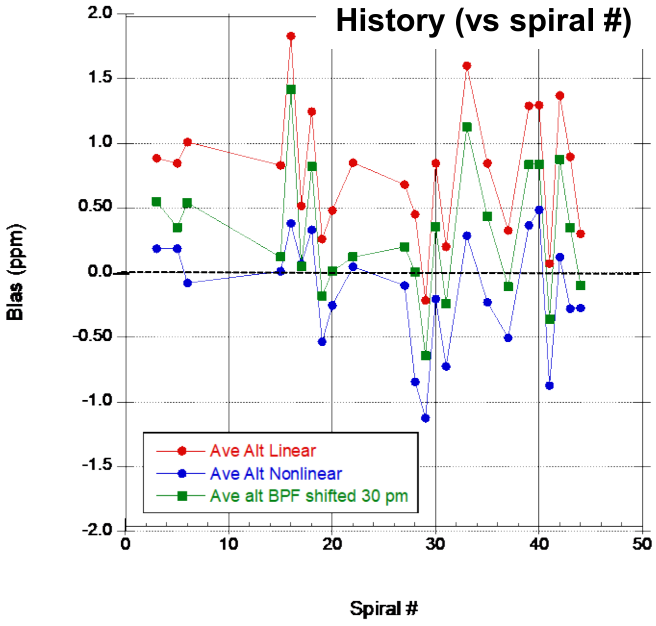
1. Correcting for linear slope
2. Correcting for quadratic shape
3. Shift filter in wavelength (done manually) & use linear correction

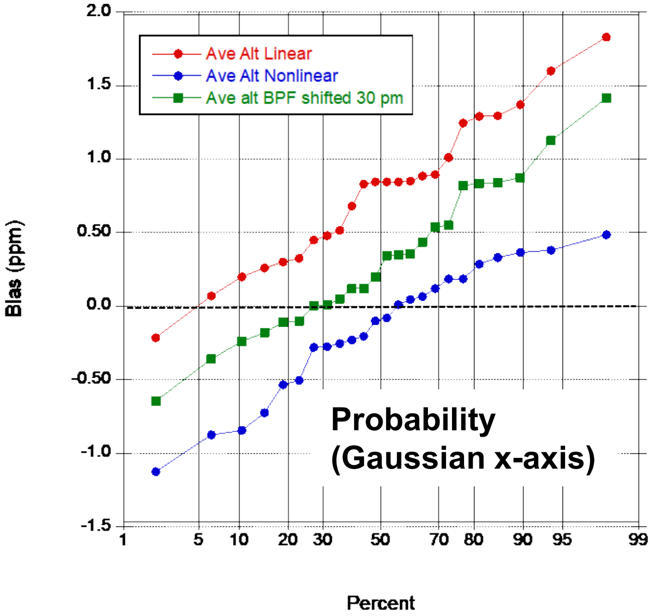
Improved approaches are practical for the future

Expanded view of Lidar's 2017 Bandpass Filter peak (red) & lidar wavelengths (blue)



Lidar XCO_2 vs *in situ* XCO_2 vs Spiral # in Campaign





Bias Statistics for Campaign (ppm)

Linear	Nonlinear	Shifted BPF
Mean diff for campaign **0.78**	Mean diff for campaign **-0.15**	Mean diff for campaign **0.31**
Std Dev of Means 0.50	Std Dev of Means 0.44	Std Dev of Means 0.50

- The + & – changes in bias (ie bias excursions) are well correlated for different line-fitting wavelength corrections
  => Deviations driven by factors not related to wavelength correction approach
- Linear fit correction has largest + excursions
- Distributions appear roughly gaussian

Summary

- The ASCENDS/ABoVE airborne campaign had 8 flights in July and August 2017.
  - 47 spiral-down maneuvers: California, NWT Canada, Arctic Ocean, Alaska, transit flights
- Performed analysis of “Bias” [XCO_2 (lidar) – (XCO_2 (in situ)] in 37 of these spirals.
- “Bias” values & statistics depended on correction for non-uniform spectral transmission in lidar receiver.
  - Using a quadratic line fit correction: lowest average bias for campaign.
    - Mean value of bias for campaign: -0.15 ppm, std. dev for campaign: 0.44 ppm
- Approaches to further reduce bias in updates to CO_2 Sounder lidar & in space version:
  - Better synchronize & check time stamps on in-situ & aircraft data sets
    - Any time offsets in 3 different data streams used cause data shifts -> ”Bias”
  - Change receiver’s optical bandpass filter to one with flatter top (less wavelength variability)
  - Sample outgoing laser energy through receiver’s optical filter (processing normalizes variability)

Questions or comments: – Please email: james.b.abshire@nasa.gov