Evaluation of Spire GNSS Radio Occultation Neutral Atmosphere and Ionosphere Products

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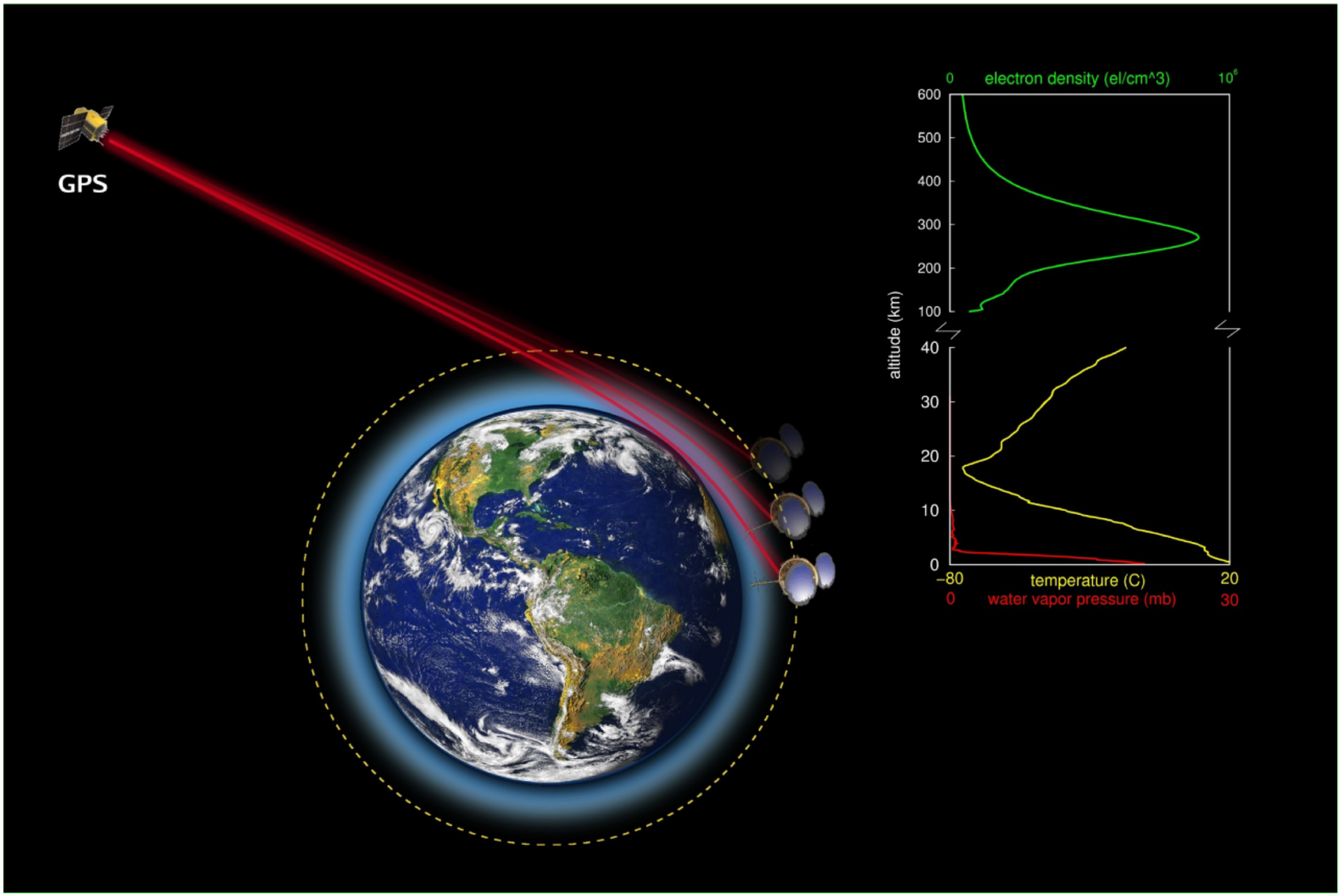
NASA CSDA Lunch-and-Learn
July 25, 2022

Outline

- Introduction and background
- Neutral atmosphere results
  - Comparisons to COSMIC-2 (C2)
  - Three-cornered hat analysis
- Ionosphere results
- Summary and lessons learned

GNSS Radio Occultation

- Radio occultation (RO) technique looks at bending of radio waves traversing an atmosphere
  - First applied to planetary atmospheres by teams at JPL and Stanford University with Mariner IV spacecraft (Kliore et al., 1965)

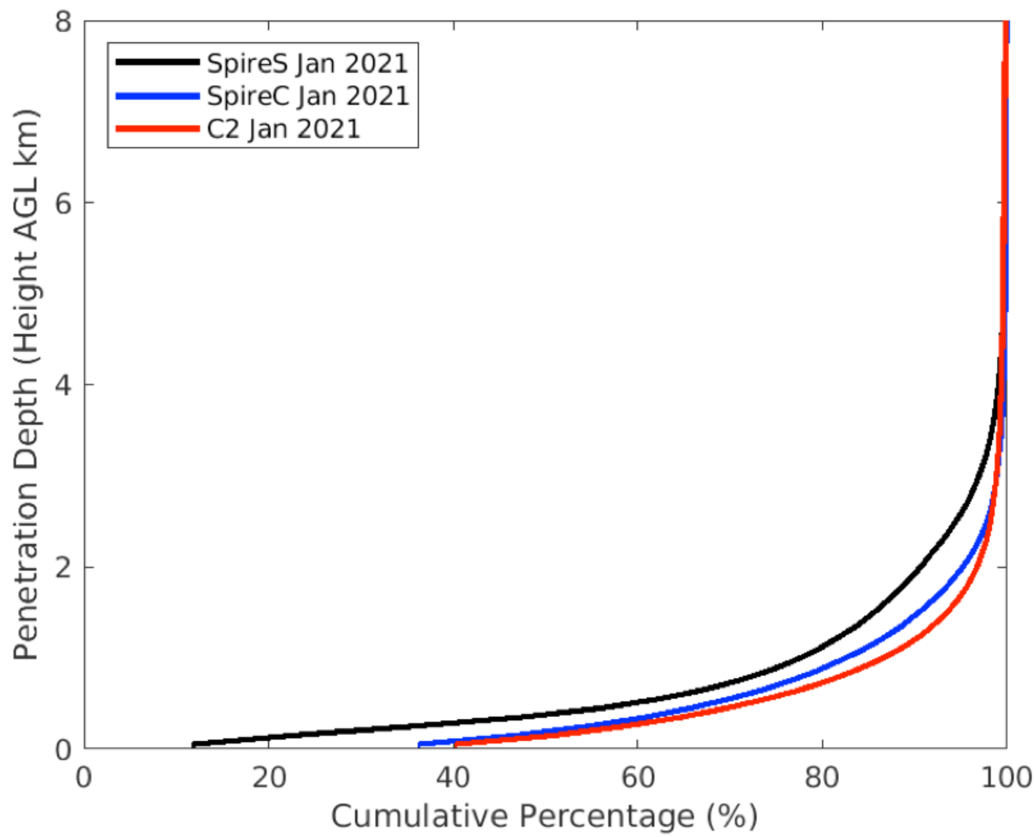


Datasets

- NASA CSDA purchasing all Spire radio occultation data with delay
  - Full dataset important to evaluate system performance
  - Large data volume interesting for science studies
  - In contrast, NOAA near real-time data purchase is not the full dataset (currently ~6K occ/day)
- For this analysis, science team focused on January 2021
- Using both Spire and COSMIC Data Analysis and Archive Center (CDAAC) generated level 2 products
  - CDAAC able to generate ~76% of Spire profiles (discussed in lessons learned)

Neutral Atm Comparisons

- Spire level 2 (SpireS) and CDAAC level 2 (SpireC)
- CDAAC retrieval penetration lower

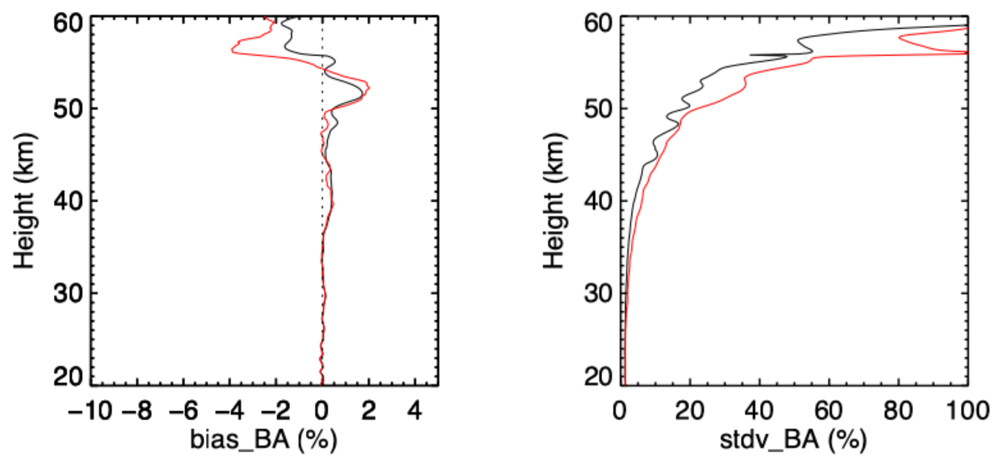


Dataset	Penetration at 1 km (%)
C2	87.5
SpireC	83.5
SpireS	78.6

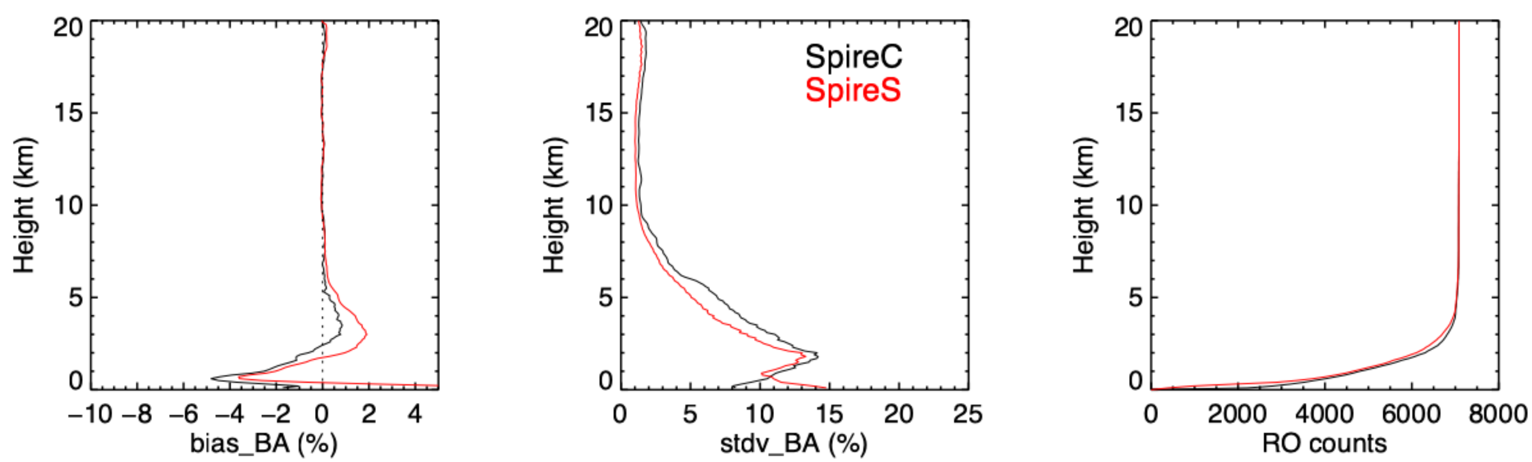
- On next two slides, profiles paired according to time, RO and reference satellites for comparisons

RO Bending Angle vs. ECMWF

- BA biases for both SpireC and SpireS ROs are comparable above 6 km
- Below 6 km, the SpireC shows smaller positive bias and larger negative bias than SpireS
- BA stdv from SpireC is smaller than that from SpireS above 20 km and larger than SpireS below 20 km

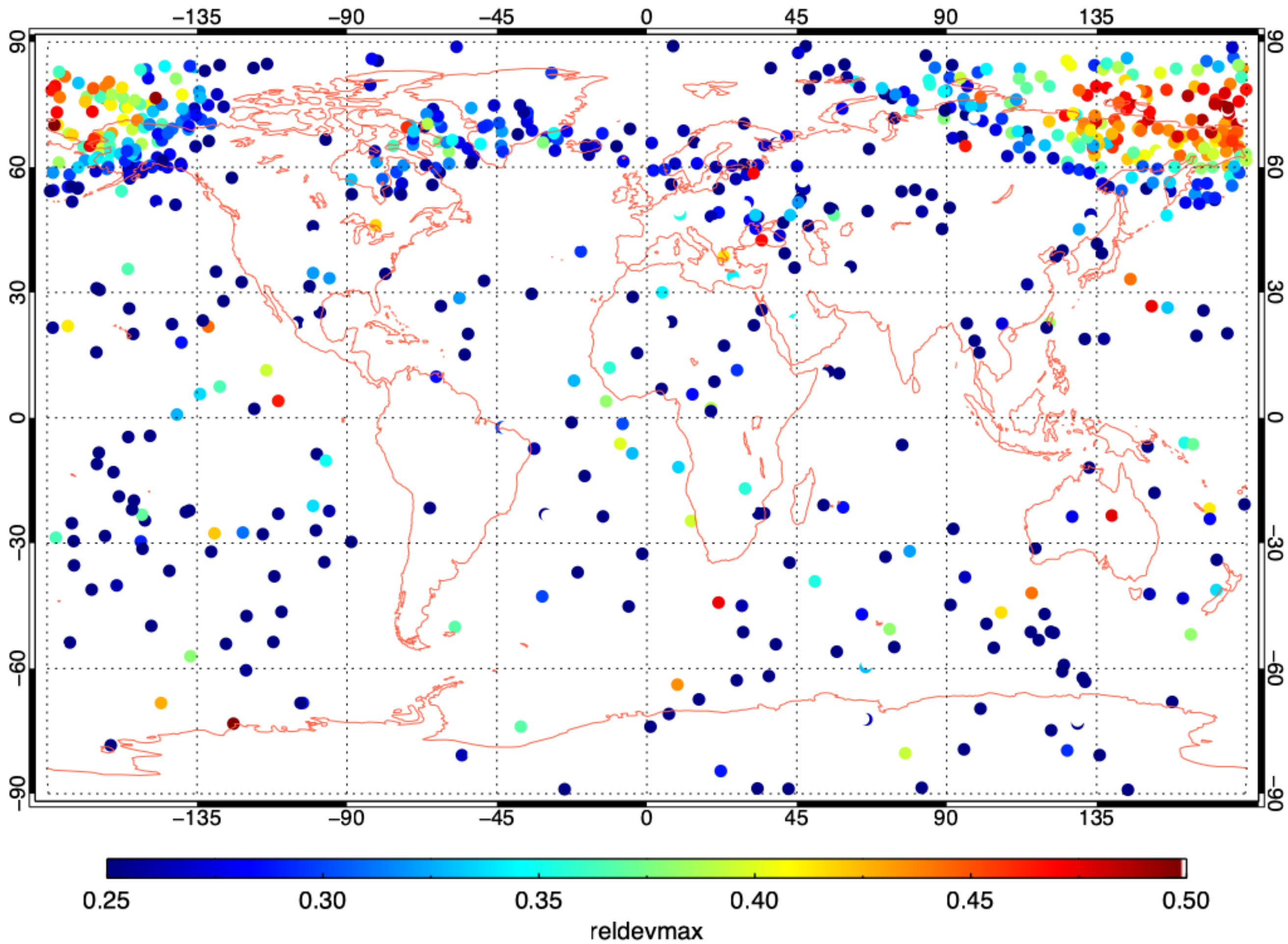


Statistics shown for 2021-01-03



Neutral Atm Retrieval QC

- If relative deviation from bending angle climatology between 20-40 km exceed 0.25, CDAAC flags profile as “bad”
  - Probably should relax threshold from 0.25 to 0.3



Data shown
for 2021-01-03

3-Cornered Hat (3CH) Analysis

- Assume a set of observations X can be written

$$X = T + \beta_X + \varepsilon_X$$

where T is Truth (set of values), β_X is the mean bias, ε_X are random errors

- With two more data sets Y and Z, we can write the error variance as

$$\text{Var}[\varepsilon_X] = \frac{1}{2}(\text{Var}[X - Y] + \text{Var}[X - Z] - \text{Var}[Y - Z])$$
$$+\text{Cov}[\varepsilon_X, \varepsilon_Y] + \text{Cov}[\varepsilon_X, \varepsilon_Z] - \text{Cov}[\varepsilon_Y, \varepsilon_Z]$$

with similar equations for Y and Z

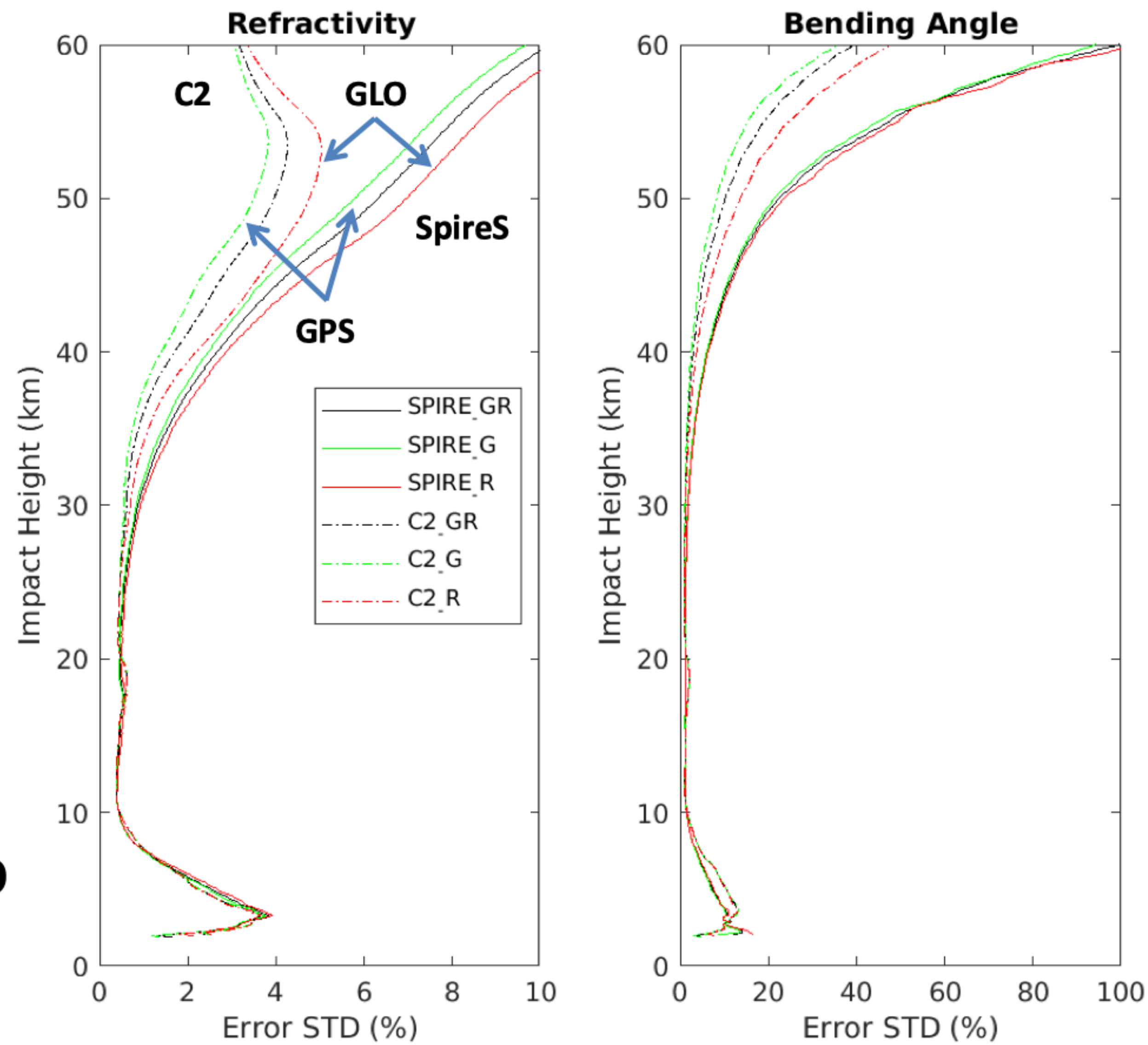
- In practice, we assume error covariance ≡ 0, and take steps to increase this likelihood

- Our work has found the 3CH method is accurate and easy to implement

- Next slides compare SpireS to C2
  - SpireC results to be added

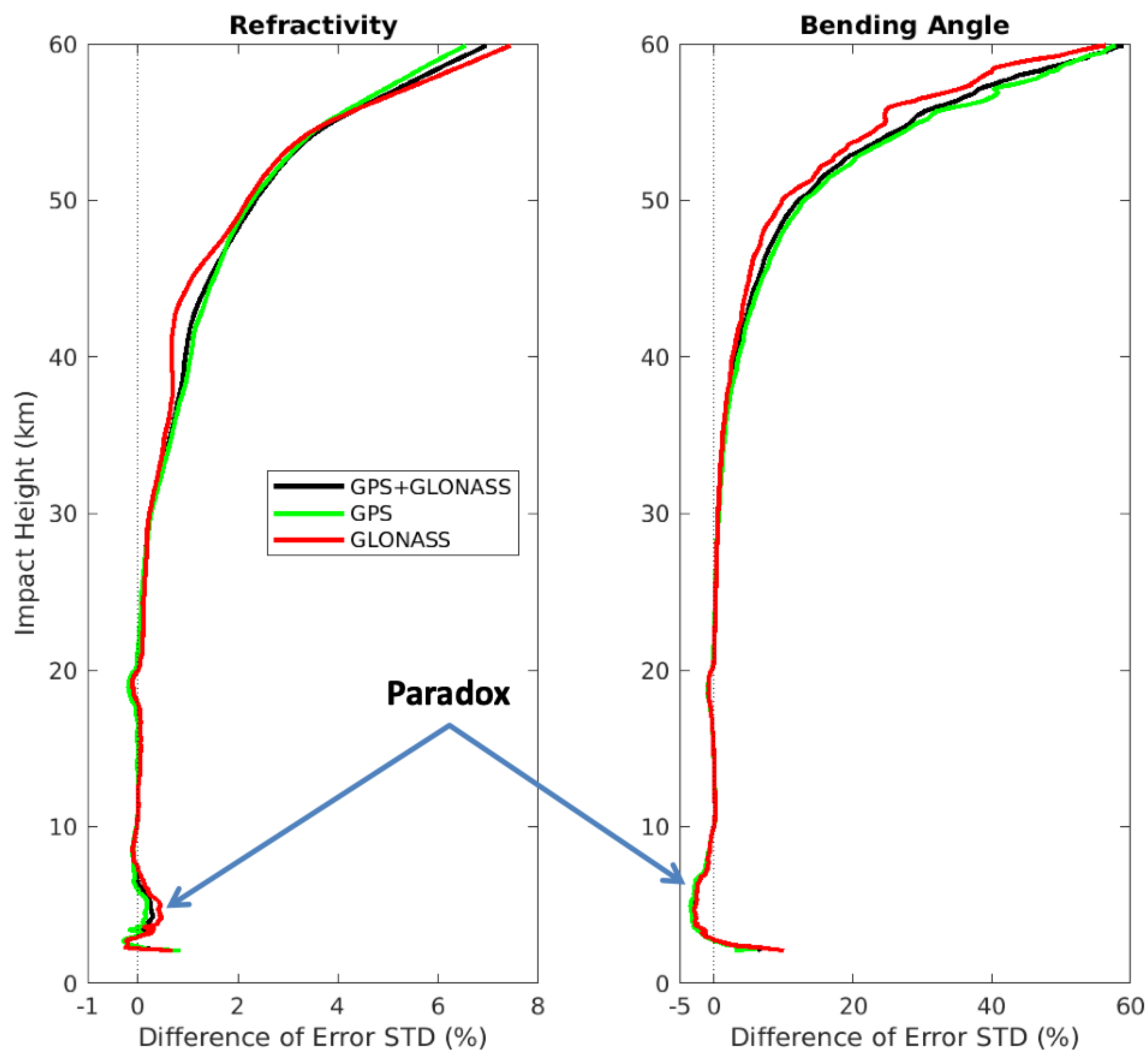
Uncertainty Estimates from 3CH

- Bending angle and refractivity error for SpireS and C2
- C2 uncertainty at higher levels smaller than SpireS
  - SpireC results pending
- Differences between GPS and GLO mainly due to transmitter clock stability



Uncertainty Estimates from 3CH

- Spire minus C2 uncertainties
- C2 has smaller BA and N uncertainties than SpireS above 40 km
- SpireS has smaller BA uncertainties between 3-8 km, larger below 3 km
  - Likely due to more vertical smoothing in Spire profiles

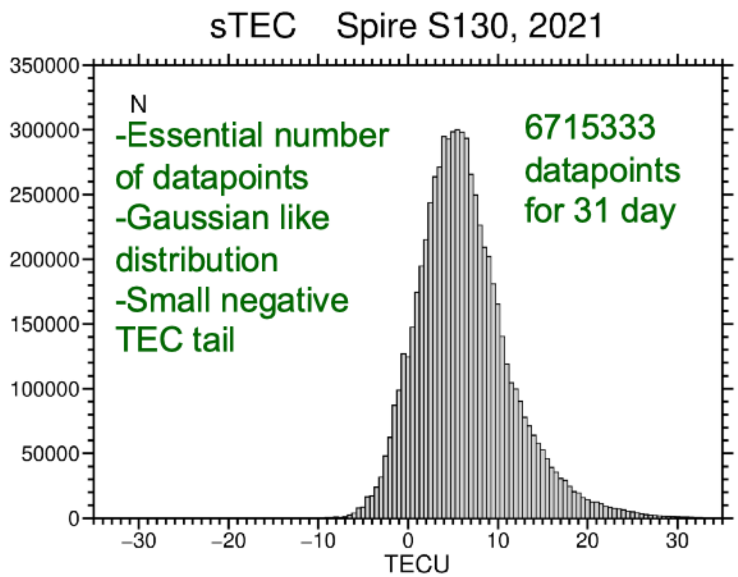


Paradox: SpireS BA uncertainties < C2 but SpireS N uncertainties > C2. Probably related to SpireS greater smoothing in vertical with greater vertical correlation of BA errors and resulting accumulation of errors in N calculation through Abel integral transform.

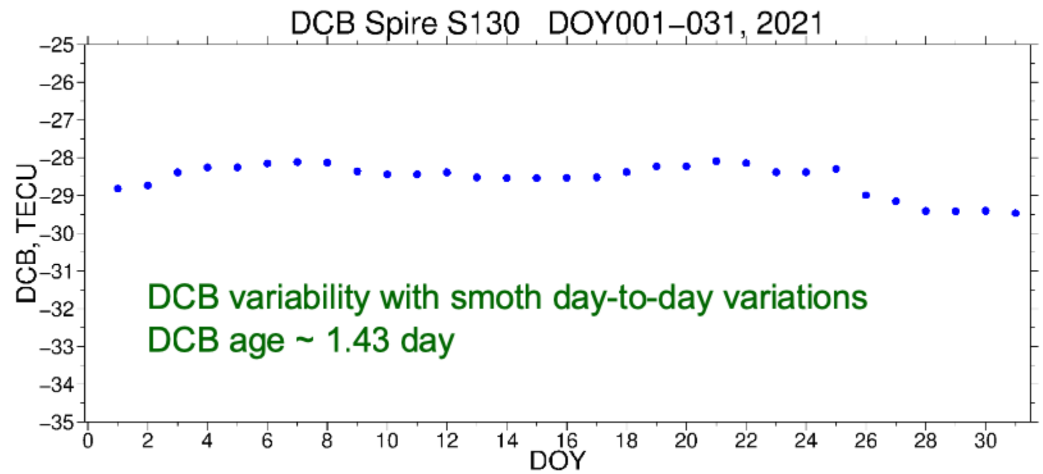
Ionosphere Results

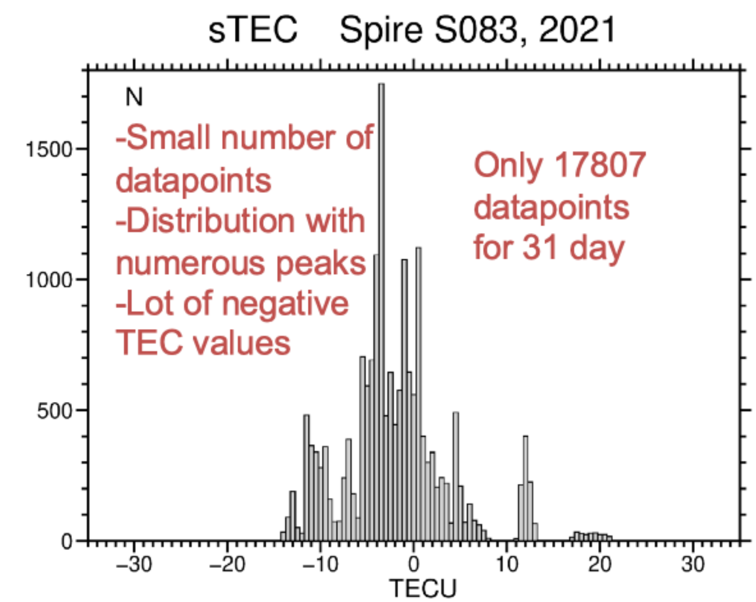
- Evaluated slant total electron content (TEC) product from Spire and CDAAC for January 2021 dataset
- Assessed
  - Differential code bias quality and temporal variation
  - Absolute TEC statistical distribution
- Key metrics for “good” TEC product found to be
  - At least 1M (SpireS) or 500K (SpireC) data points per month per FM
  - DCB age less than 5 days

Spire Product Quality Examples

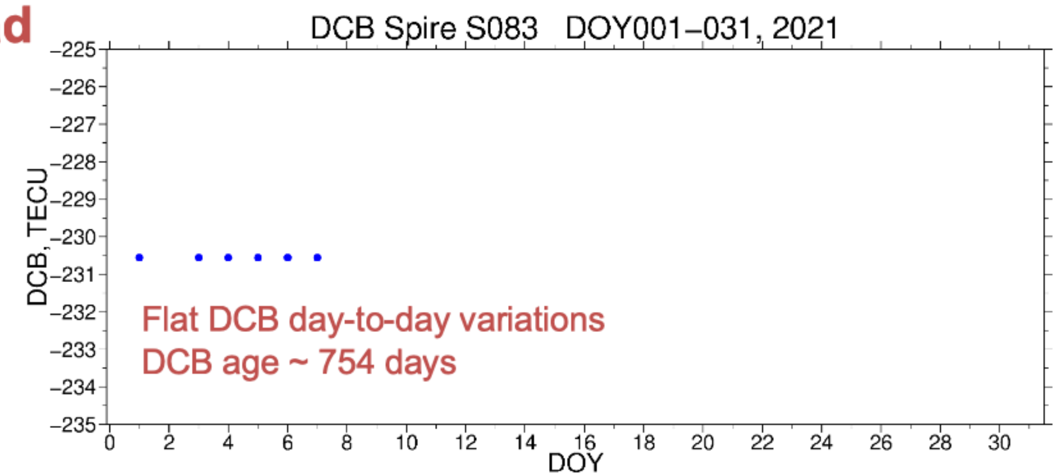


OK



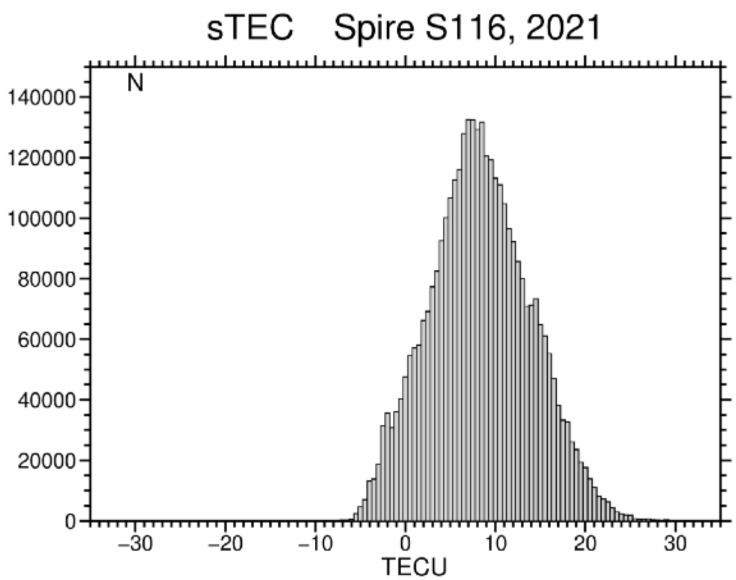


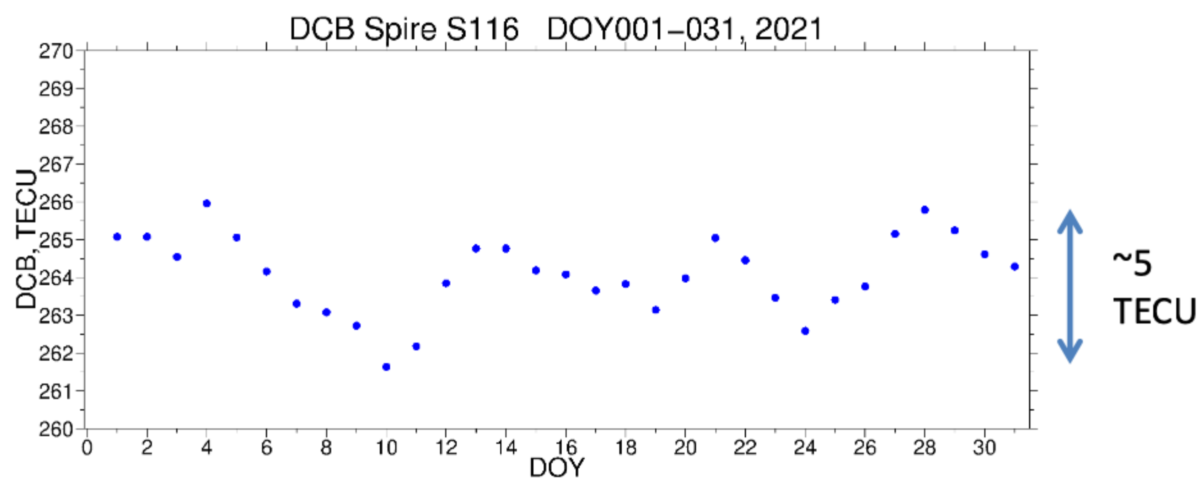
Bad

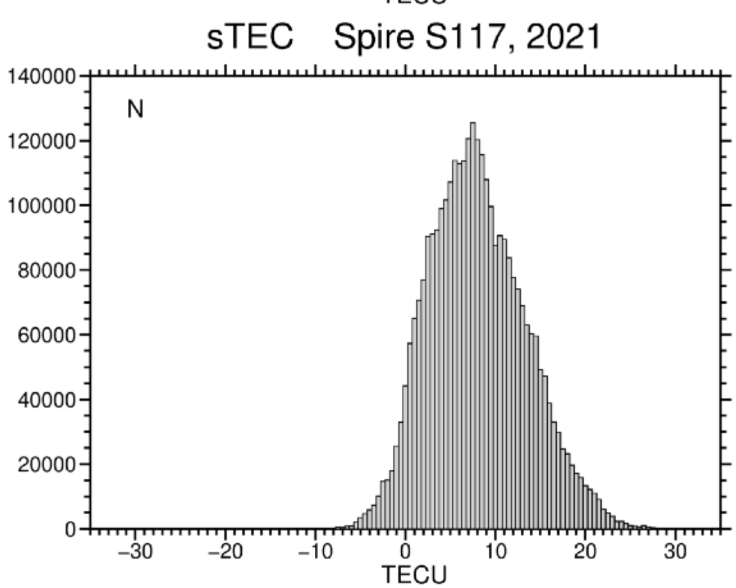


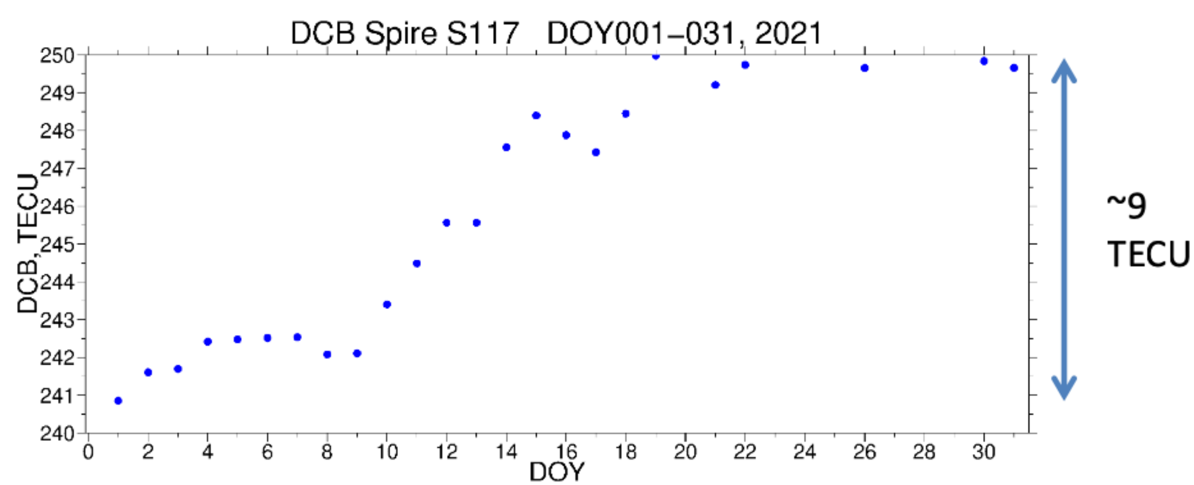
CDAAC TEC and DCB Examples

- Example FMs yield reasonable sTEC distributions









TEC Quality Summary

- 25 good FMs included in Spire products, 27 good FMs in CDAAC products
- Sample FM list below (all are in backup slides)

January 2021, CDAAC

FM	Altitude	DCB quality	sTEC quality	Data points number	DCB age
102	525	ok	ok	4787479	0
103	570	ok	ok	1008268	0.01
104	570	ok	ok	6093126	0
106	570	ok	ok	1653067	0
107	570	ok	ok	6483074	0
108	570	ok	ok	6035031	0
109	none	none	none	none	none
110	none	none	none	none	none
113	570	ok	ok	1996443	0.04
115	575	ok	ok	2234152	0
116	561	ok	ok	3554378	0
117	575	ok	ok	3194079	0
118	561	ok	ok	2524224	0
119	584	ok	ok	407309	0
120	561	ok	ok	3591510	0
121	562	ok	ok	282078	0.068
122	562	ok	ok	2403326	0
124	562	ok	ok	1847152	0

January 2021, Spire

FM	Altitude	DCB quality	sTEC quality	Data points number	DCB age
102	525	ok	ok	13537482	1.321
103	570	ok	ok	2880466	1.339
104	570	ok	ok	14718310	1.306
106	570	ok	ok	4213504	1.38
107	570	ok	ok	16353145	1.228
108	570	ok	ok	16419303	1.291
109	580	ok	ok	6031712	1.752
110	580	ok	bad	1499005	1.535
113	570	ok	ok	4740619	1.237
115	575	ok	ok	5358136	1.292
116	561	ok	ok	9396659	1.303
117	575	ok	ok	10316528	1.369
118	561	ok	ok	7467856	1.347
119	584	bad	bad	896873	1.234
120	561	ok	ok	9039128	1.319
121	562	ok	bad	594332	7.539
122	562	ok	ok	8720922	1.252
124	562	ok	ok	4892409	1.421

Conclusions

- Data processing algorithms and quality control procedures impact product counts, penetration, and uncertainties
- CDAAC able to process most of the low level Spire data into products
  - Retrieval results in deeper penetration and lower uncertainties vs. ECMWF at higher altitudes
  - Some optimizations identified
- 3CH analysis comparing SpireS and C2
  - C2 has deeper penetration than SpireS
  - C2 has smaller uncertainties above 30 km than SpireS
  - C2 and SpireS comparison mixed in troposphere
  - Overall C2 and SpireS similar below 30 km
- Ionosphere results generally reasonable for both processing centers
  - Some differences in FMs yielding good TEC statistics

Lessons Learned

- Data fetching from CSDA data explorer is challenging
  - Manual interface not well suited to fetching thousands of files per day
  - Access to daily tar file for each data type e.g. scp/wget would be more efficient
- CDAAC processing
  - POD data provided do not always cover +/- 2 hours around occultation
    - Results in POD problems
    - Main cause for CDAAC producing ~76% of Spire occultations
  - Reldevmax QC
    - Tuning identified to be tested

Backup

TEC Quality Summary

January 2021, CDAAC

FM	Altitude	DCB quality	sTEC quality	Data points number	DCB age
53	600	none	none	none	none
61	490	none	none	none	none
75	590	none	none	none	none
79	600	ok	ok	584078	0.234
80	580	none	none	none	none
81	470	none	none	none	none
82	470	none	none	none	none
83	480	none	none	none	none
84	485	ok	ok	852070	0.121
85	470	none	none	none	none
86	490	none	none	none	none
87	515	bad	bad	88606	0.166
88	none	none	none	none	none
90	480	none	none	none	none
99	530	ok	ok	4063281	0
100	525	ok	ok	2064536	0
101	525	ok	ok	3627734	0

January 2021, Spire

FM	Altitude	DCB quality	sTEC quality	Data points number	DCB age
53	600	bad	bad	49186	467.741
61	490	bad	bad	55773	428.188
75	590	bad	bad	37426	364.842
79	600	ok	ok	2322917	2.417
80	580	bad	bad	25882	313.962
81	470	bad	bad	32778	452.389
82	470	bad	bad	493	852.251
83	480	bad	bad	17807	754.855
84	485	ok	ok	2157109	1.291
85	470	bad	bad	77091	281.495
86	490	bad	bad	84212	566.375
87	515	bad	bad	331187	5.013
88	none	none	none	none	none
90	480	bad	bad	13452	281.174
99	530	ok	ok	14057737	1.307
100	525	ok	ok	9910166	3.34
101	525	ok	ok	10544767	1.342

TEC Quality Summary

January 2021, CDAAC

FM	Altitude	DCB quality	sTEC quality	Data points number	DCB age
102	525	ok	ok	4787479	0
103	570	ok	ok	1008268	0.01
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107	570	ok	ok	6483074	0
108	570	ok	ok	6035031	0
109	none	none	none	none	none
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TEC Quality Summary

January 2021, CDAAC

FM	Altitude	DCB quality	sTEC quality	Data points number	DCB age
125	562	ok	ok	4941870	0
126	none	none	none	none	none
127	none	none	none	none	none
128	576	ok	ok	2508718	0
129	584	ok	ok	2671528	0
130	581	ok	ok	1037356	0.098
131	581	ok	ok	1240704	0.024
132	none	none	none	none	none
133	none	none	none	none	none
134	none	none	none	none	none
135	none	none	none	none	none
136	none	none	none	none	none
142	none	none	none	none	none
143	none	none	none	none	none
145	none	none	none	none	none
146	none	none	none	none	none
147	none	none	none	none	none
148	none	none	none	none	none
150	none	none	none	none	none

January 2021, Spire

FM	Altitude	DCB quality	sTEC quality	Data points number	DCB age
125	562	ok	ok	14343749	1.199
126	none	none	none	none	none
127	none	none	none	none	none
128	576	ok	ok	5530352	1.017
129	584	ok	ok	5422124	1.239
130	581	ok	ok	6715333	1.42
131	581	ok	ok	6938890	1.34
132	none	none	none	none	none
133	none	none	none	none	none
134	none	none	none	none	none
135	none	none	none	none	none
136	none	none	none	none	none
142	none	none	none	none	none
143	none	none	none	none	none
145	414	bad	bad	109474	54.149
146	565	bad	bad	0	64.477
147	none	none	none	none	none
148	none	none	none	none	none
150	none	none	none	none	none