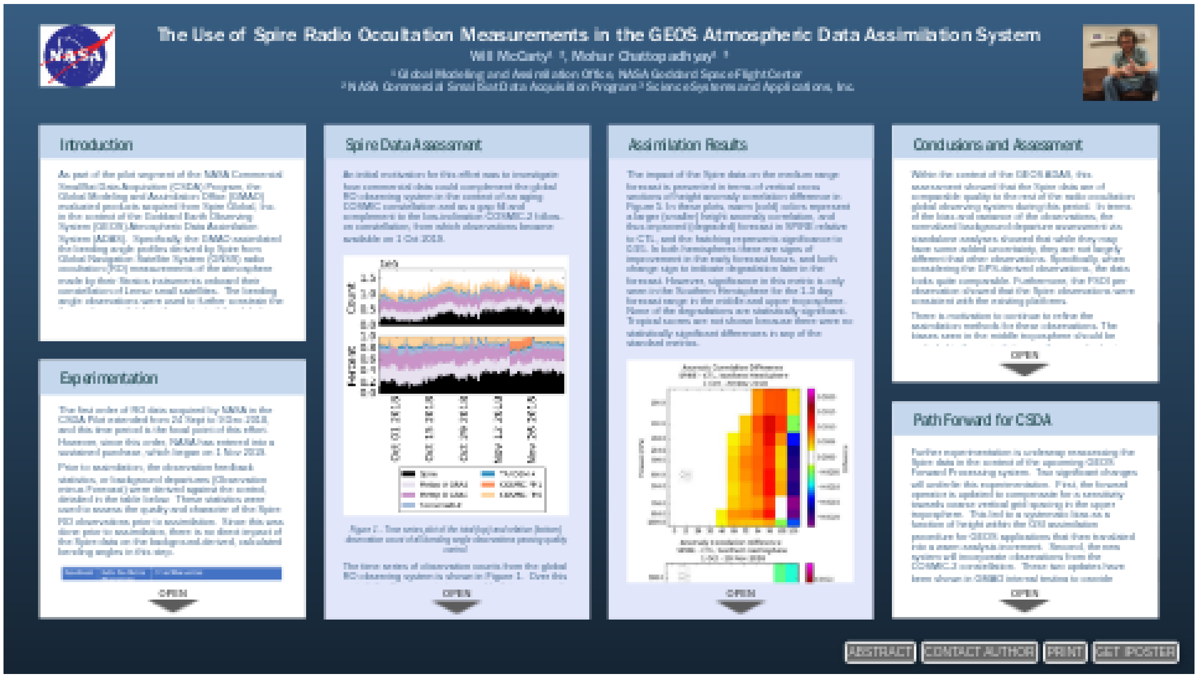
The Use of Spire Radio Occultation Measurements in the GEOS Atmospheric Data Assimilation System



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PRESENTED AT:

INTRODUCTION

As part of the pilot segment of the NASA Commercial SmallSat Data Acquisition (CSDA) Program, the Global Modeling and Assimilation Office (GMAO) evaluated products acquired from Spire Global, Inc. in the context of the Goddard Earth Observing System (GEOS) Atmospheric Data Assimilation System (ADAS). Specifically, the GMAO assimilated the bending angle profiles derived by Spire from Global Navigation Satellite System (GNSS) radio occultation (RO) measurements of the atmosphere made by their Stratos instruments onboard their constellation of Lemur small satellites. The bending angle observations were used to further constrain the thermodynamic fields in the context of the global observing system typically assimilated within GEOS.

EXPERIMENTATION

The first order of RO data acquired by NASA in the CSDA Pilot extended from 24 Sept to 9 Dec 2018, and this time period is the focal point of this effort. However, since this order, NASA has entered into a sustained purchase, which began on 1 Nov 2019.

Prior to assimilation, the observation feedback statistics, or background departures (Observation minus Forecast) were derived against the control, detailed in the table below. These statistics were used to assess the quality and character of the Spire RO observations prior to assimilation. Since this was done prior to assimilation, there is no direct impact of the Spire data on the background-derived, calculated bending angles in this step.

Experiment	Radio Occultation Observations	Other Observations
CTL	GRAS (Metop-A, -B) COSMIC TerraSAR-X TANDEM-X	Conventional Surface Conventional Upper-Air Aircraft Satellite-Derived Winds (AMVs, ASCAT) Clear-sky Infrared (AIRS, IASI, CrIS) Clear-sky Microwave (AMSU-A, MHS, ATMS, SSMIS) All-Sky Microwave (GPM GMI) Retrieved Ozone (OMI, MLS)
SPIRE	CTL + Spire	CTL

After assessing the RO data quality, the Spire data were then assimilated using a standard Observing System Experiment (OSE) methodology, as indicated by the SPIRE experiment above. The forward operator and assimilation methodology was generally consistent with that the other radio occultation measurements.

All experimentation leverage the GEOS ADAS version 5.22.0p1. The GEOS model segment is run on a nominal 1/4 degree, C360 horizontal grid with 72 layers extending to 0.01 hPa. The analysis was performed using the GSI procedure on a 0.5 x 0.625 degree geographic lat-lon grid using the same vertical levels. Analysis results are from a Hybrid 4D-EnVar solution using an hourly first-guess at analysis time (FGAT), and the model forecasts are intialized using a 4D-Incremental Analysis Update.

SPIRE DATA ASSESSMENT

An initial motivation for this effort was to investigate how commercial data could complement the global RO observing system in the context of an aging COSMIC constellation and as a gap fill and complement to the low-inclination COSMIC-2 follow-on constellation, from which observations became available on 1 Oct 2019.

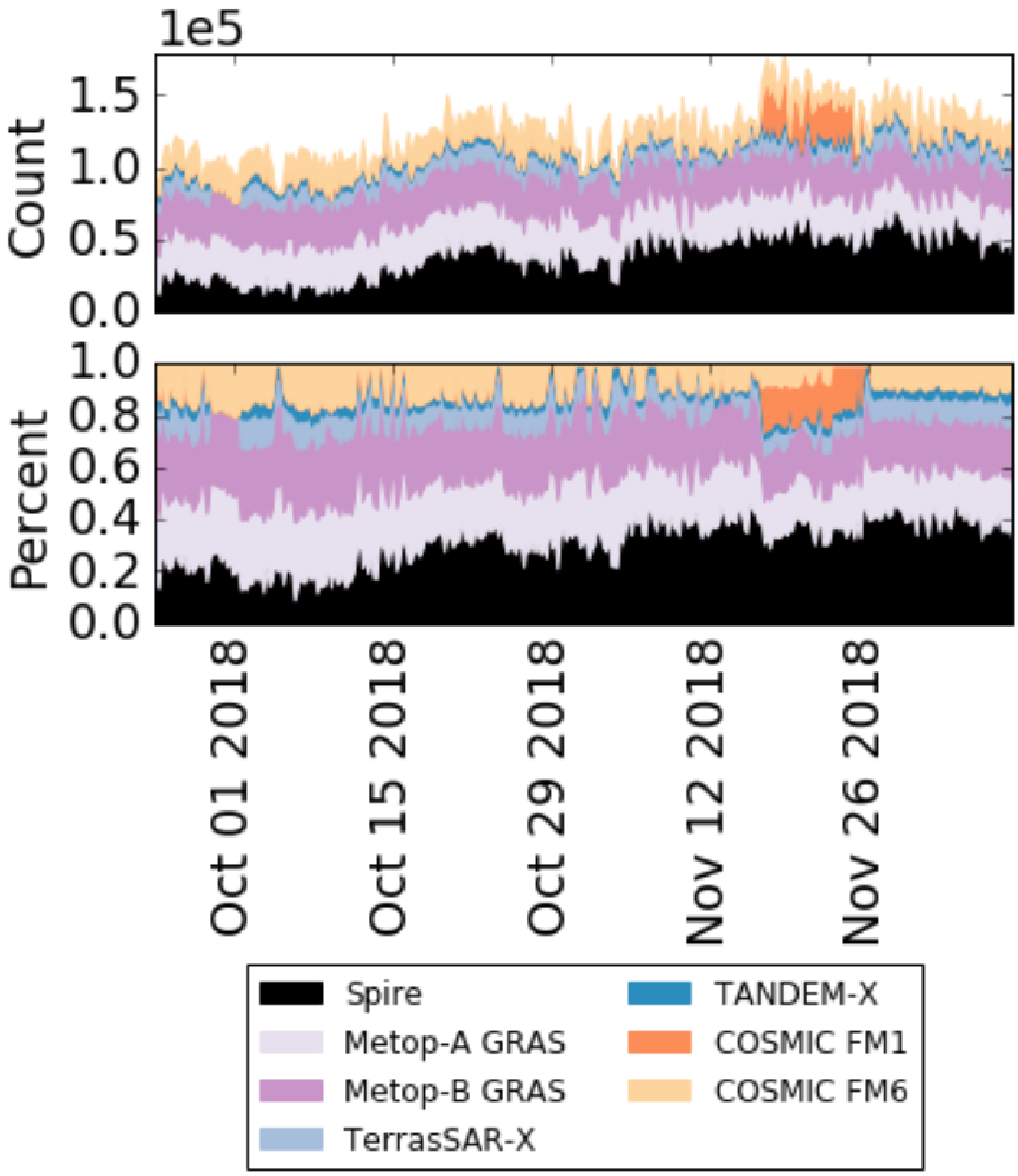


Figure 1 - Time series plot of the total (top) and relative (bottom) observation count of all bending angle observations passing quality control.

The time series of observation counts from the global RO observing system is shown in Figure 1. Over this period, the Spire counts increased both in count and relative contribution to all RO data. Quantitatively, this accounted for Spire ranging from 20% early in the period to 40% later, as the data counts were increasing through the study period.

The observing system is dominated by the Metop GRAS instruments. Both Metop satellites sit in sun-synchronous orbit with a 2130 Local Time of the Ascending Node (LTAN). Thus, these observations tend to exist in the same location in each 6-hour assimilation window. This is illustrated in Figure 2 by considering the relative contribution of Spire data to the global RO observing system spatially.

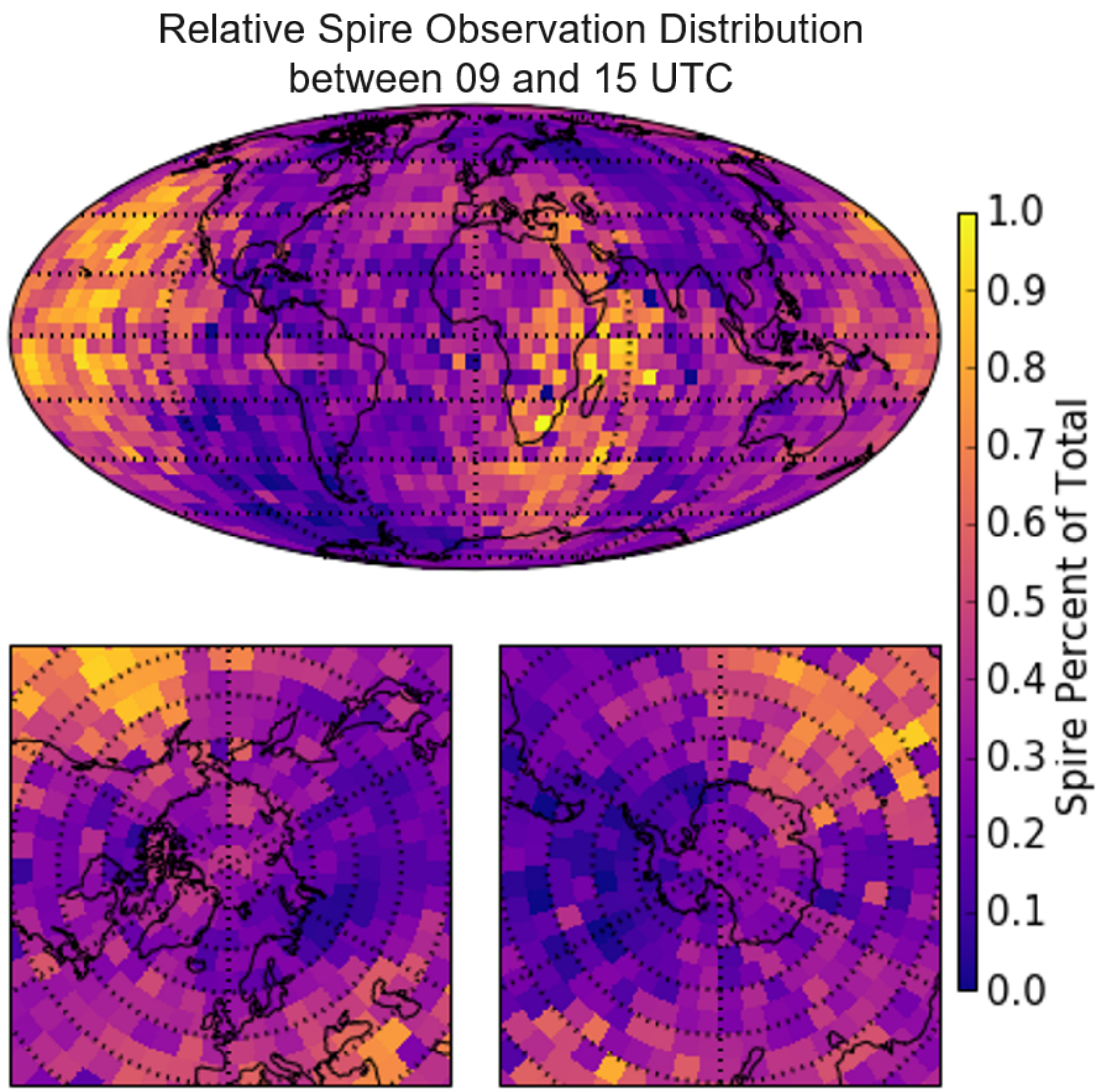


Figure 2 - The percent Spire observations relative to the total RO observing network over 6 hour periods centered 12 UTC

While the Spire data was shown to represent 20-40% of all data globally, the spatial distribution shows that when coincident with the Metop data, the relative percentages are low, ranging from 30% and less. However, for the regions uncovered by Metop, the percent of observations often exceeds 70%. This shows that Spire's constellation has the capability of not only providing a large number of RO profiles, but it also has the capability to fill data voids left by the existing observing systems.

Background departures were analyzed to compare the quality of the Spire bending angle profiles, as shown for 0-60 km (top) and 0-10 km (bottom) in Figure 3.

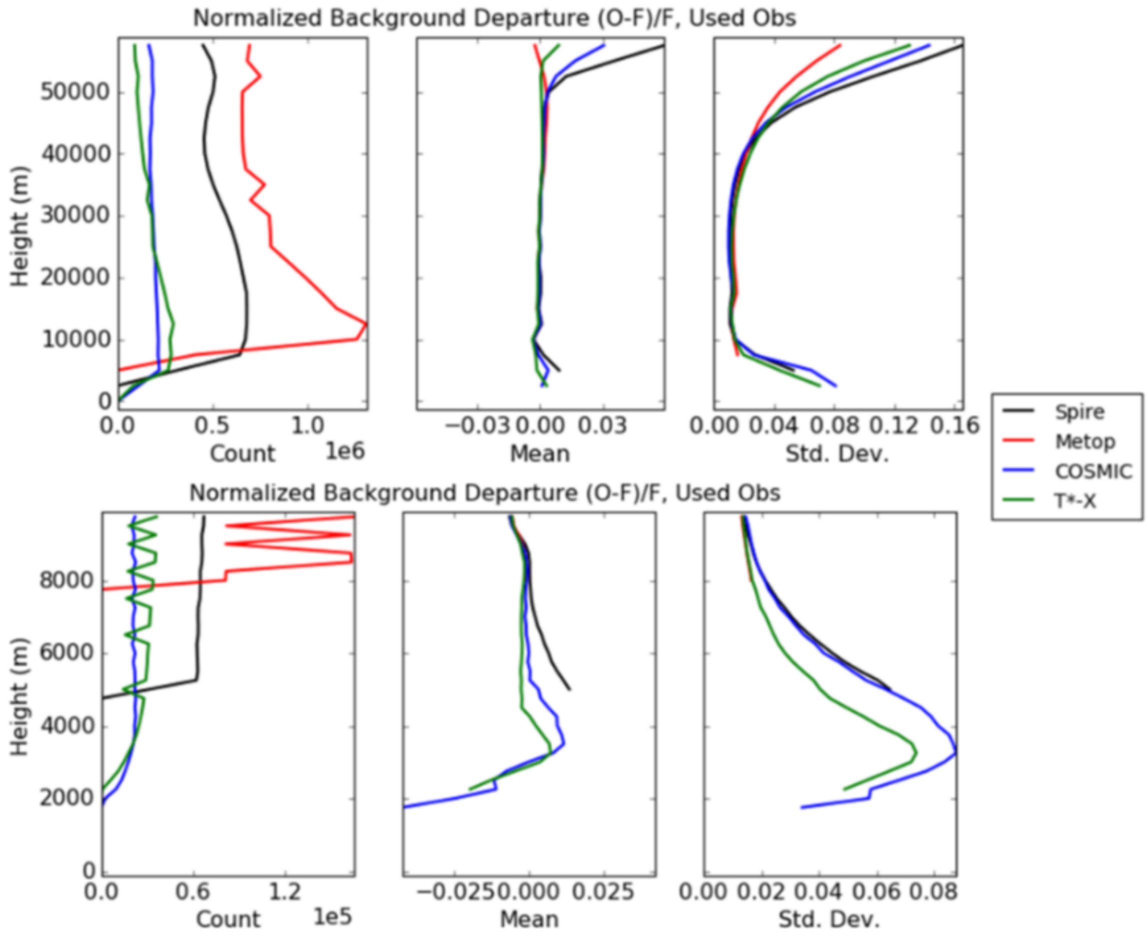


Figure 3 - Vertical profiles of the observation count (left), the normalized background departure mean (center) and standard deviation (right) for the full column (top) and from 0 km to 10 km (bottom), as a function of observing platform.

In the upper-stratosphere and lower-mesosphere, the Spire data exhibited more bias and variance compared to the other observing systems. There are two key points to this. First, ionospheric effects damped the information content in mass-space above 40 km for all RO observations. Second, the model does not fully represent the physics of the mesosphere, so there are noted biases and uncertainties above the stratopause. These uncertainties have temporal scales that will vary by orbit. However, through most of the stratosphere, the Spire observations are consistent with the other observing systems.

When focusing on the troposphere, it is noted that the Spire and COSMIC observations exhibit similar standard deviations, particularly below 10 km. However, the Spire data exhibits more bias in the background departures than the COSMIC data. This bias is seen to grow as it reaches an imposed 5 km height cutoff.

However, one unique feature of the Spire data compared to the other observing systems in this period are that they perform radio occultation from multiple GNSS sources. COSMIC only utilized signals transmitted from the US Global Positioning System (GPS), but Spire uses signals transmitted from the Russian Global Navigation Satellite System (GLONASS) and the Japanese Quasi-Zenith Satellite System (QZSS) system in addition to GPS. The background departures for Spire relative to each transmitting source is shown in Figure 4.

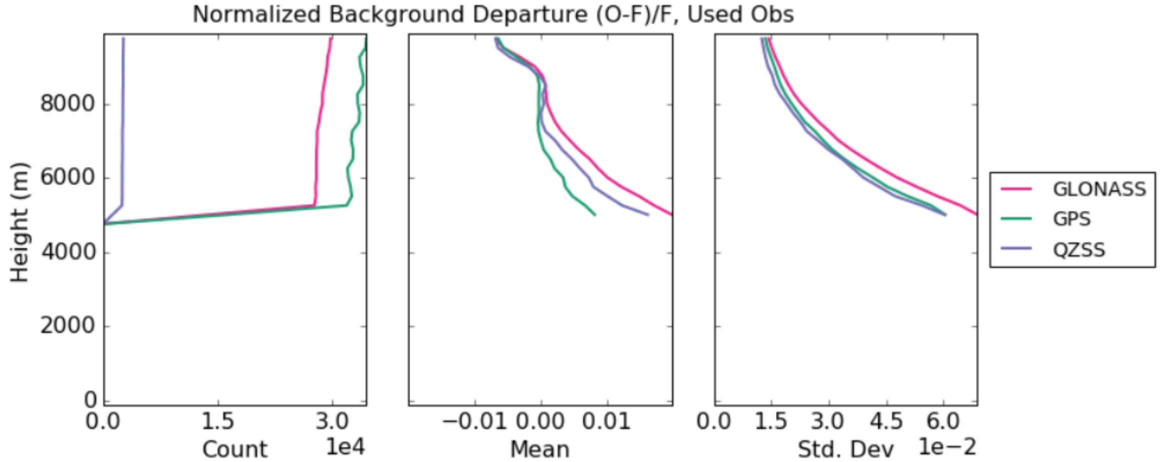
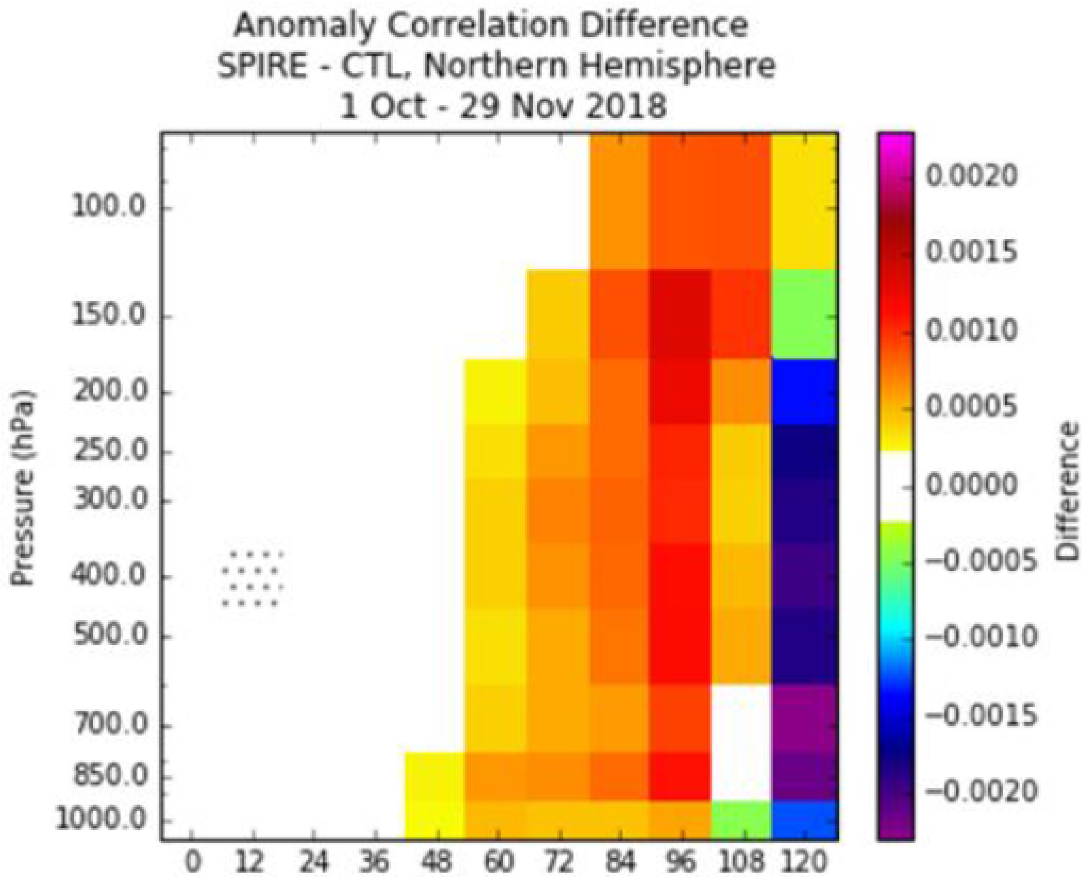


Figure 4 - Vertical profiles of the observation count (left), the normalized background departure (center) mean, and standard deviation (right) from 0 km to 10 km, as a function of GNSS emitting source.

The GLONASS-derived bending angle profiles are more variant, and that their background departure bias starts at a higher altitude and increases towards the surface. The bias in the GPS-derived observations is more in-line with those from COSMIC.

ASSIMILATION RESULTS

The impact of the Spire data on the medium range forecast is presented in terms of vertical cross sections of height anomaly correlation difference in Figure 5. In these plots, warm (cold) colors represent a larger (smaller) height anomaly correlation, and thus improved (degraded) forecast in SPIRE relative to CTL, and the hatching represents significance to 0.95. In both hemispheres there are signs of improvement in the early forecast hours, and both change sign to indicate degradation later in the forecast. However, significance in this metric is only seen in the Southern Hemisphere for the 1-3 day forecast range in the middle and upper troposphere. None of the degradations are statistically significant. Tropical scores are not shown because there were no statistically significant differences in any of the standard metrics.


Anomaly Correlation Difference
SPIRE - CTL, Northern Hemisphere
1 Oct - 29 Nov 2018
Pressure (hPa)
100.0
150.0
200.0
250.0
300.0
400.0
500.0
700.0
850.0
1000.0
0
12
24
36
48
60
72
84
96
108
120
0.0020
0.0015
0.0010
0.0005
0.0000
−0.0005
−0.0010
−0.0015
−0.0020
Difference

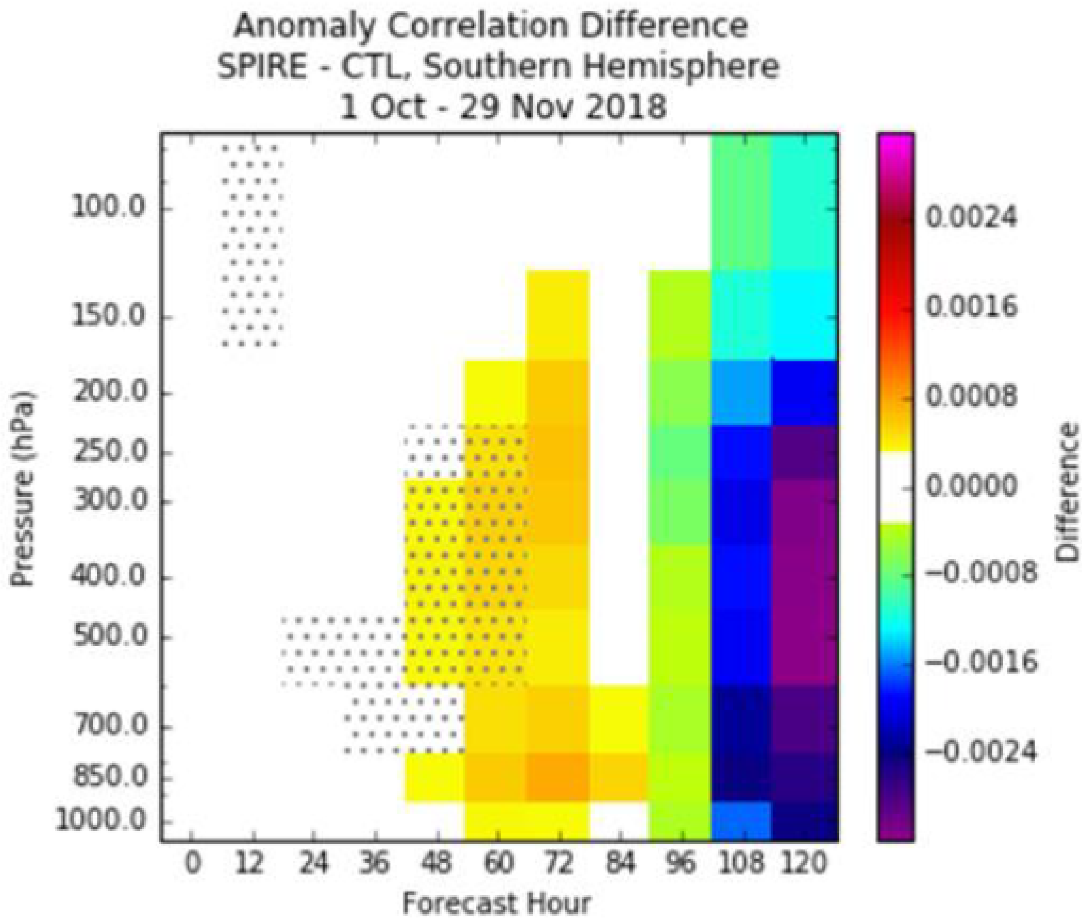

Anomaly Correlation Difference
SPIRE - CTL, Southern Hemisphere
1 Oct - 29 Nov 2018
Pressure (hPa)
100.0
150.0
200.0
250.0
300.0
400.0
500.0
700.0
850.0
1000.0
0
12
24
36
48
60
72
84
96
108
120
Forecast Hour
0.0024
0.0016
0.0008
0.0000
−0.0008
−0.0016
−0.0024
Difference

Figure 5 - Northern (top) and Southern (bottom) Hemisphere vertical profiles of forecast height anomaly correlation difference, (SPIRE minus CTL). Negative values indicate a forecast degradation. The hatching represent the 0.95 confidence interval.

Next, the Spire data was considered in the context of the forecast sensitivity observation impact (FSOI, Langland and Baker 2004, Zhu and Gelaro 2009) metric. This metric is a quantification of how each measurement acts to reduce or increase the 24 hour forecast error. Since the metric is calculated per datum, it can be aggregated in numerous ways to further assess the observations as a function of their metadata. The relative count and FSOI of the RO observations in the SPIRE experiment are shown in Figure 6. The ratios of the observing system assimilated counts (left) and the ratio of the FSOI to the total RO FSOI (right) are very similar. Since these are similar, all the observing systems carry a similar FSOI per observation (center). Though not shown, the similarity per observation was also seen as a function of height.

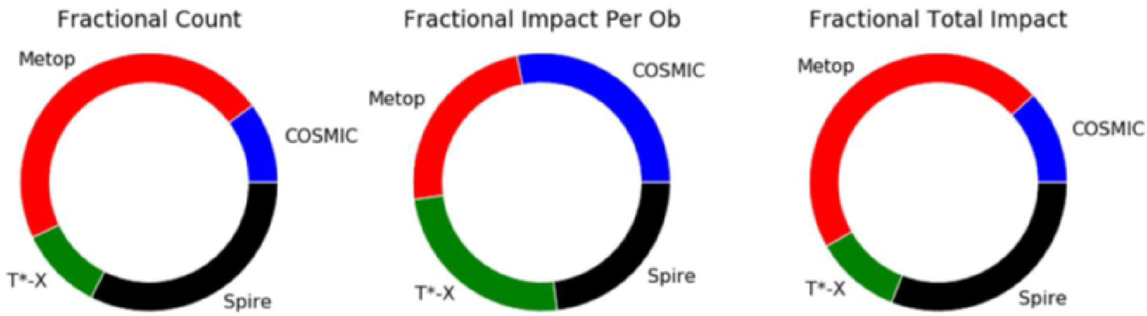


Figure 6 - The RO observation fractional count (left), fractional FSOI per observation (center), and the Fractional Total FSOI (right).

Finally, FSOI is presented for the Spire observations as a function of height and the originating source of the RO signal, as shown in Figure 7. QZSS has relatively few observations, and this results in a small total FSOI and an irregular vertical profile per observation. The GPS-derived bending angles result in a smoother vertical profile of FSOI compared to GLONASS, even though the counts are of similar magnitude. This perhaps corresponds to the higher variance and bias seen previously.

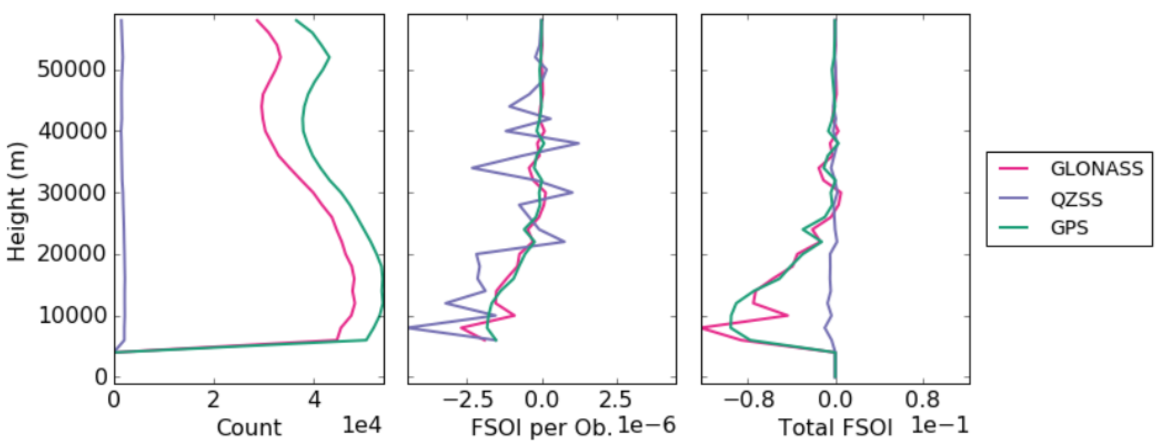


Figure 7 - Vertical profiles of count (left), FSOI per observation (center) and Total FSOI (right), for Spire observations separated by GNSS emitting source.

CONCLUSIONS AND ASSESSMENT

Within the context of the GEOS ADAS, this assessment showed that the Spire data are of comparable quality to the rest of the radio occultation global observing system during this period. In terms of the bias and variance of the observations, the normalized background departure assessment via standalone analyses showed that while they may have some added uncertainty, they are not largely different that other observations. Specifically, when considering the GPS-derived observations, the data looks quite comparable. Furthermore, the FSOI per observation showed that the Spire observations were consistent with the existing platforms.

There is motivation to continue to refine the assimilation methods for these observations. The biases seen in the middle troposphere should be excluded in the assimilation, as they may be having negative feedbacks onto the system, and the threshold should vary based on GNSS signal source. There were no statistically significant degradations seen, but there were some degradations that approached significance. If these could be mitigated by improved vertical thresholding, then it more improvement may be seen.

PATH FORWARD FOR CSDA

Further experimentation is underway reassessing the Spire data in the context of the upcoming GEOS Forward Processing system. Two significant changes will underlie this experimentation. First, the forward operator is updated to compensate for a sensitivity towards coarse vertical grid spacing in the upper troposphere. This led to a systematic bias as a function of height within the GSI assimilation procedure for GEOS applications that then translated into a warm analysis increment. Second, the new system will incorporate observations from the COSMIC-2 constellation. These two updates have been shown in GMAO internal testing to provide statistically significant improvements.

In the recent transition within the CSDA program from the pilot evaluation to a sustained purchase, the Spire data volume has also increased dramatically. Thus, there is an expectation that RO measurements will play a more significant role in upcoming GEOS systems. As such, this last batch of testing is essentially to the optimal use of these commercial data.

ABSTRACT

This study evaluates the role of Spire Level 2 bending angle profiles in the context of the Goddard Earth Observing System (GEOS) Atmospheric Data Assimilation System (ADAS) and other RO observing systems. Initial assessment, as part of the NASA Commercial SmallSat Data Acquisition Program (CSDAP) showed that the Spire observations were generally consistent and complementary to existing radio occultation observing systems. In terms of quantity, the Spire observations accounted for ~20-40% of the total RO observing system. Additionally, these new observations were complementary to the other GNSS-RO observing systems in that they filled spatial data voids due to their broad global sampling. Statistically, the observations were found to be comparable to other RO observing systems, though there was a tropospheric bias in those observations derived from the GLONASS GNSS signals. Their forecast impacts were found to be comparable to other RO observing systems. No statistically significant impact on medium range forecast (2+ days) was seen, but there was a quantifiable reduction on short-term (24 hour) forecast error via the FSOI metric. These results, including any additional results in the context of the most recent CSDAP Spire data purchase, will be presented.