# SPIRE/STRATOS (GNSS-RO) Quality Assessment Summary


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*EDAP.REP.017* *Issue: 1.2* *10/07/20*

## AMENDMENT RECORD SHEET

The Amendment Record Sheet below records the history and issue status of this document.

| ISSUE | DATE | REASON |
|---|---|---|
| 1.0 | 05/02/20 | First Issue |
| 1.1 | 25/03/20 | Reviewed Issue |
| 1.2 | 10/07/20 | Updated as per ESA review/comments |

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## TABLE OF CONTENTS

# 1. ACRONYMS

| | |
|---|---|
| AIS | Automatic identification System |
| GPS | Global Positioning System |
| GNSS | Global Navigation Satellite System |
| LT | Lower Troposphere |
| MEO | Middle Earth Orbit |
| POD | Precise Orbit Determination |
| RO | Radio Occultation |
| RS | Radiosonde |

# 2. INTRODUCTION

SPIRE Global is a data and Analytics Company that designs, builds, tests, operates and collects data from its satellite constellation composed of Lemur-2 satellites. Each of these satellites carry two payloads: STRATOS GPS radio occultation meteorology payload and SENSE AIS payload for ship tracking.

STRATOS is the SPIRE GNSS receiver for remote sensing & precision orbit determination:

- Performs POD (Precise Orbit Determination) using the zenith L1, L2 antenna;
- Performs radio occultation (RO) on high-gain, side-mounted L1, L2 antennas;
- Currently enables atmospheric & ionospheric remote sensing;
- Applications: weather model assimilation of RO, space weather monitoring, ionosphere corrections for navigation, thermospheric density (POD);
- Currently modifying STRATOS for passive bistatic radar (GNSS-R) applications.

STRATOS makes use of GPS occultation measurements to determine temperature, pressure and humidity profiles of Earth's atmosphere for application in operational meteorology.

The instrument consists of GPS receivers to track the signals of several MEO satellites and measure the time delay and bend angle of signals that travel through the atmosphere located in the line of sight of the two spacecraft.

These phase delay measurements due to refraction by the atmosphere can be made from the satellite altitude to very close to the surface leading to precise information on the properties of the atmosphere at an accurate vertical resolution.

GNSS-RO is a technique that provides unique temperature, pressure, and moisture vertical soundings through the atmosphere, similar to the type of data collected by a weather balloon.

The L2 Products provided are representing the "dry" temperature, pressure (~ 6 - 70 km, although climatology dominates above ~50 km), "wet" temperature, pressure, and water vapor pressure (< 6 km), with the following characteristics:

- Vertical sounding resolution: ~100 m
- Along-track resolution: ~200 km
- Across-track resolution: ~1 km
- Accuracy: ~0.5 K
- Vertical resolution: ~5 Pa

# 3. QUALITY ASSESSMENT MATRIX

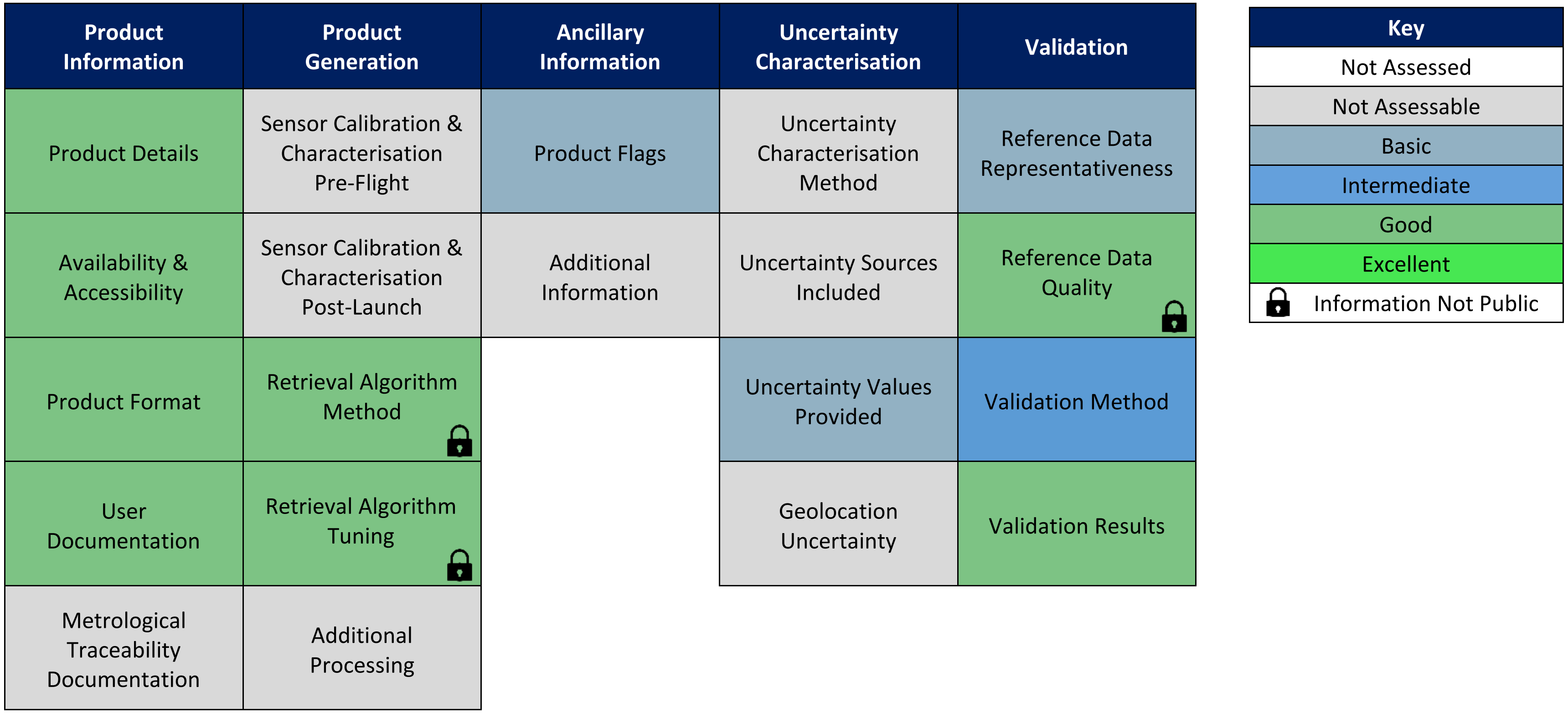



**Figure 1 – SPIRE Product Quality Evaluation Matrix.**

# 4. ASSESSMENT OVERVIEW

## 4.1 Product Information

| Product Details | |
|---|---|
| Product Name | *GNSS-RO* |
| Sensor Name | *STRATOS (GNSS-RO)* |
| Sensor Type | *GPS receivers to track the signals of several MEO satellites* |
| Mission Type | *Constellation ~80 Nanosatellites* |
| Mission Orbit | *Multiple Orbits at c.a. 530 km of altitude* |
| Product Version Number | *v1* |
| Product ID | *atmPrf* |
| Processing level of product | *Level-2* |
| Measured Quantity Name | *Bending Angle, Temperature, Refractivity* |
| Measured Quantity Units | *Degrees, K.* |
| Stated Measurement Quality | *e.g. stated 2% radiometric accuracy* |
| Spatial Resolution | *c.a. 100 meters in altitude* |
| Spatial Coverage | *Atmospheric Profiles – Global Coverage* |
| Temporal Resolution | c.a. 0.3 sec. |
| Temporal Coverage | 1 month of data |
| Point of Contact | SPIRE Global |
| Product locator (DOI/URL) | https://www.spire.com/en/spire/about-spire-global |
| Conditions for access and use | Commercial Data, conditions defined by contract |
| Limitations on public access | N/A (conditions defined by contract) |
| Product Abstract | Ref. to https://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=atmPrf |

| Availability & Accessibility | |
|---|---|
| Compliant with FAIR principles | *Yes* |
| Data Management Plan | *Not available to users.* |
| Availability Status | *There is no catalogue available online, but data can be requested through an API. Data availability defined by contract.* |

| Product Format | |
|---|---|
| Product File Format | *netCDF4 and .bufr*<br>- *Ref. to Spire Product Specifications* |
| Metadata Conventions | *e.g. v1* |
| Analysis Ready Data? | *No* |

| User Documentation | | |
|---|---|---|
| *Document* | *Reference* | *QA4ECV Compliant* |
| Product User Guide | *Spire Level 2 Product README File* | *Partially* |
| ATBD | Spire Level 2 Algorithm Theoretical Baseline Document v1.0 | Yes |

| Metrological Traceability Documentation | |
|---|---|
| Document Reference | *N/A* |
| Traceability Chain / Uncertainty Tree Diagram Available | *NO* |

## 4.2 Product Generation

| Sensor Calibration & Characterisation – Pre-Flight | |
|---|---|
| Summary | *Receiver Qualified, but no details available.* |
| References | • *(Jeroen Cappaert) Building, Deploying and Operating a Cubesat Constellation - Exploring the Less Obvious Reasons Space is Hard, 32nd AIAA/USU Conference on Small Satellites, August 4-9 2018.*<br>• *(Adriian Perez Portero, Ruiz De Azúa Ortega, Juan AdriánMés informacióMés informació; Camps Carmona, Adriano JoséMés informacióMés informació; Muñoz Martin, Joan FrancescMés informacióMés informació) Design, Implementation and Verification of Cubesat Systemsfor Earth Observation; 2019-05-26 (http://hdl.handle.net/2117/134850)* |

| Sensor Calibration & Characterisation – Post-Launch | |
|---|---|
| Summary | GNSS *phase measurement = no drift, no* calibration, *no inter-instrument biases. Anyway, in the processing chain there is Open-loop tracking of both setting and rising RO events* |
| References | • *Seizing Opportunity: Spire's CubeSat Constellation ofGNSS, AIS, and ADS-B Sensors (Dallas Masters, I07-Masters-Spire_GNSS_AIS_ADS-B.pdf), Stanford PNT Symposium, 2018-11-08* |

| Retrieval Algorithm Method *(Include for Level 2 Products Only)* | |
|---|---|
| Summary | Geometric optical (GO) processing is the first stage of the RO data processing. It serves for the initial evaluation of the occultation parameters and smooth models of the Doppler frequency shift and phase excess.<br>Ionospheric Correction and bend angle determination.<br>Abel Transformation and refractivity determination.<br>Determination of atmospheric products (model inversion). |
| References | • *Spire Level 2 Processing Input_Output Data Definition v1.0*<br>• *Spire Level 2 Algorithm Theoretical Baseline Document* |

| Retrieval Algorithm Tuning *(Include for Level 2 Products Only)* | |
|---|---|
| Summary | Non-spherical symmetry Turbulence, strong convection, noise Super-refraction conditions |
| References | • *(Lidia Cucurull) Global Positioning System (GPS) Radio Occultation (RO) Data Assimilation, GSI/EnKF Community Tutorial, 11-14 August 2015*<br>• *Seizing Opportunity: Spire's CubeSat Constellation of GNSS, AIS, and ADS-B Sensors, (I07-Masters-Spire_GNSS_AIS_ADS-B.pdf)* |

| Additional Processing | |
|---|---|
| Description | *N/A* |
| Reference | *N/A* |

## 4.3 Ancillary Information

| Product Flags | |
|---|---|
| Product Flag Documentation | *Product with Bad Flag* |
| Comprehensiveness of Flags | *Yes* |

| Ancillary Data | |
|---|---|
| Ancillary Data Documentation | *N/A* |
| Comprehensiveness of Data | *N/A* |
| Uncertainty Quantified | *NO* |

## 4.4 Uncertainty Characterisation

| Uncertainty Characterisation Method | |
|---|---|
| Summary | *N/A* |
| Reference | *N/A* |

| Uncertainty Sources Included | |
|---|---|
| Summary | *There is no uncertainty source included.* |
| Reference | *N/A* |

| Uncertainty Values Provided | |
|---|---|
| Summary | *The bending angle standard deviation is provided inside the product* |
| Reference | *Ref. to "Bend_ang_stdv" parameter*<br>*Spire Product Specifications v1.0 document* |
| Analysis Ready Data? | *No* |

| Geolocation Uncertainty | |
|---|---|
| Summary | *N/A* |
| Reference | *N/A* |

## 4.5 Validation

| Validation Activity #1 | |
|---|---|
| Independently Assessed? | Yes |
| *Reference Data Representativeness* | |
| Summary | *Dataset has been defined by contract with Spire and it is a month of data (profiles) distributed over the globe. It represents a very small representative dataset, just to assess a high level and preliminary quality assessment.* |
| Reference | *1 month SPIRE data (2019-05-26/2019-06-25)* |
| *Reference Data Quality & Suitability* | |
| Summary | *In the core region (stratosphere), Spire data is highly consistent with IGRA radiosondes.* |
| Reference | • *This note*<br>• *(Neill Bowler) Initial assessment of GNSS-RO data from Spire, IROWG19*<br>• *(Christian Marquardt) Assessment of Spire Commercial RO Data* |
| *Validation Method* | |
| Summary | *Two verifications have been considered:*<br>- *Intercomparison with collocated data from IGRA Network*<br>- *Review of literature and presented studies.* |
| Reference | • *IGRA Network Data*<br>• *(Neill Bowler) Initial assessment of GNSS-RO data from Spire*<br>• *(Christian Marquardt) Assessment of Spire Commercial RO Data* |
| *Validation Results* | |
| Summary | In the core region (stratosphere), Spire data is highly consistent with IGRA radiosondes; the particular, this occur for specific range of altitude where data are not always comparable:<br>• *0 - 5 Km - Near 5 km (where Moisture is significant);*<br>• *12 - 13 Km – Tropopause;*<br>• *35 - 40 Km – Upper Stratosphere.* |
| Reference | • *(Dallas Masters) Status and Plans for Spire's Growing Commercial Constellation of GNSS Science CubeSats*<br>• *(Neill Bowler) Initial assessment of GNSS-RO data from Spire*<br>• *(Christian Marquardt) Assessment of Spire Commercial RO Data*<br>• *(Vu Nguyen) Space Weather Observations from Spire's Growing CubeSat Constellation* |

# 5. DETAILED ASSESSMENT

In the present study IGRA data have been compared with SPIRE data.

The analysis has been performed using one month of SPIRE data (2019-05-26/2019-06-25) and IGRA 2019 radiosonde profiles. The colocation of profiles to be compared have been realized considering from each IGRA station (Lat/Lon) a 300 km square and SPIRE data inside the square have been compared with IGRA data, with a time constraint of ± 3h.

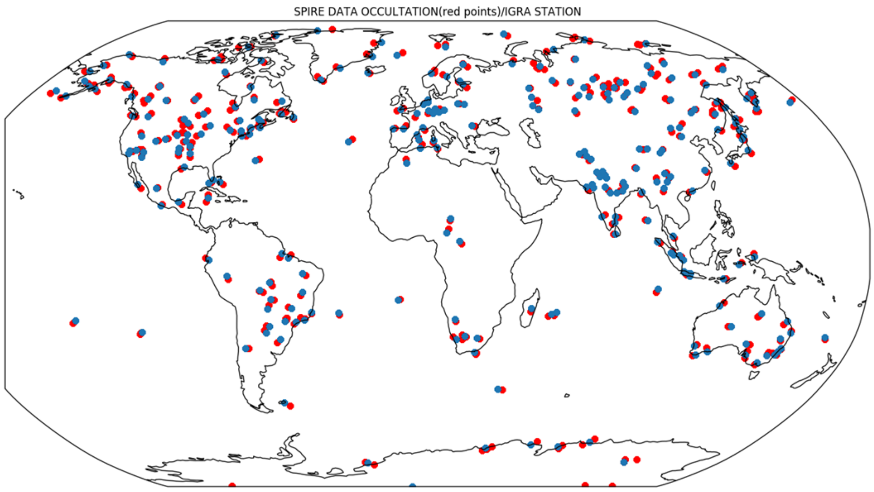



**Figure 2: IGRA data (blue) and Spire data (red)**

In a square of 300 Km with a time constraint of ± 3h, 363 products have been compared (Figure 2).

## 5.1 ALTITUDE-TEMPERATURE COMPARISON

Spire data files are organized in .netcdf format as we can see in the below figure.

Panoply: Panoply — Sources

File Edit View History Bookmarks Plot Window Help

Create Plot Combine Plot Open Dataset

Datasets Catalogs Bookmarks

| Name | Long Name | Type |
|---|---|---|
| atmPrf_2019-05-27T21-26-38Z.2226020.091.G30.nc | atmPrf_2019-05-27T21-26-38Z.2226020.091.G30.nc | Local File |
| azim | Azimuth of perigee plane at occultation point with respect to North | — |
| Azim | Azimuth angle of the occultation plane with respect to North | 1D |
| bad | Badness flag. 1 = Profile flunked quality control, 0 = Profile passed QC | — |
| Bend_ang | Raw (unoptimized) bending angle | 1D |
| Bend_ang_stdv | Raw bending angle standard deviation | 1D |
| bScore | Badness score [bScore<35 == good] | — |
| curv | The X, Y, and Z offset of the center of sphericity from the center of mass of the Earth | 1D |
| errstr | OK or error message | — |
| Impact_parm | Impact parameter from center of curvature | 1D |
| Lat | Latitude of perigee point | 1D |
| lat | Latitude of perigee point at occultation point | — |
| Lon | Longitude of perigee point | 1D |
| lon | Longitude of perigee point at occultation point | — |
| MSL_alt | Mean sea level altitude | 1D |
| Opt_bend_ang | Optimized bending angle | 1D |
| Opt_bend_ang_stdv | Optimized bending angle standard deviation | 1D |
| Pres | Dry pressure | 1D |
| R_GNSS | Transmitter location | 2D |
| R_LEO | Receiver location | 2D |
| Ref | Refractivity | 1D |
| rfict | Local curvature radius of the reference ellipsoid | — |
| rgeoid | Height of the geoid above the reference ellipsoid | — |
| start_time | Starting time for the occultation | — |
| stop_time | Ending time for the occultation | — |
| Temp | Dry temperature | 1D |

**Figure 3: Spire data structure (.netcdf format)**

IGRA data files are organized in file ".txt" (Figure 4).

Each column represents a measurement (Temperature, Pressure, Altitude etc…)

AFM00040948-data - Notepad

File Edit Format View Help

```
#AFM00040948 2018 01 01 00 2300   96 ncdc-gts ncdc-gts  345500   692167
21 -9999  82200B-9999     -1B-9999   160   310    21
20 -9999  81800 -9999     20B-9999   180 -9999 -9999
20 -9999  81500 -9999     20B-9999   180 -9999 -9999
20 -9999  79100 -9999     48B-9999   250 -9999 -9999
20 -9999  78900 -9999 -9999 -9999 -9999   210    51
20 -9999  75000 -9999 -9999 -9999 -9999     0     0
20 -9999  72900 -9999     16B-9999   240 -9999 -9999
10 -9999  70000  3087B    -9B-9999   230   345    26
20 -9999  67700 -9999 -9999 -9999 -9999   310    15
20 -9999  64900 -9999 -9999 -9999 -9999   345    57
20 -9999  62900 -9999    -79B-9999   210   330    77
20 -9999  57800 -9999 -9999 -9999 -9999   335   159
20 -9999  54600 -9999   -135B-9999   240 -9999 -9999
10 -9999  50000  5680B  -195B-9999   190   335   180
20 -9999  44800 -9999   -263B-9999   160 -9999 -9999
10 -9999  40000  7300B  -311B-9999   220   325   257
20 -9999  39900 -9999 -9999 -9999 -9999   325   262
20 -9999  39100 -9999   -321B-9999   230 -9999 -9999
20 -9999  33600 -9999 -9999 -9999 -9999   335   221
20 -9999  33200 -9999   -425B-9999   120 -9999 -9999
20 -9999  31400 -9999 -9999 -9999 -9999   330   226
20 -9999  30800 -9999   -459B-9999   130 -9999 -9999
10 -9999  30000  9270B  -449B-9999   180   330   319
20 -9999  28900 -9999 -9999 -9999 -9999   330   386
20 -9999  25700 -9999 -9999 -9999 -9999   325   442
10 -9999  25000 10470B  -501B-9999   200   330   427
20 -9999  23200 -9999 -9999 -9999 -9999   335   396
```

**Figure 4: IGRA data structure**

A python algorithm has been made to read and compare IGRA/Spire data.

In the figure 5, the profiles of Spire altitude [Km] / temperature [K] using direct altitude measurement (blue dots) and altitude obtained from pressure measurement (green dots) were plot, together with the altitude [Km] / temperature [K] for an IGRA station. Red dots represent IGRA data, blue dots SPIRE data and green dots represent SPIRE altitude obtained from pressure data.

As we can see in figure 5, there is a bias between SPIRE Altitude/Temperature and SPIRE Altitude (from Pressure)/Temperature. To compare SPIRE/IGRA data, the SPIRE altitude obtained from pressure has been used (figure 6).

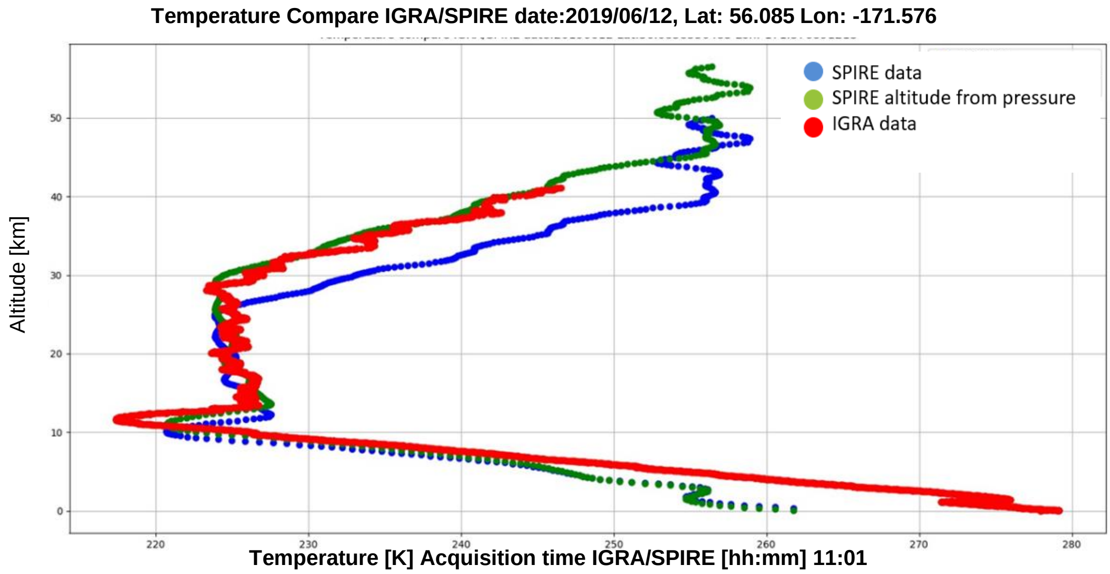



**Figure 5: Temperature compare IGRA/SPIRE with altitude obtained from pressure**

Under 5 Km of altitude, the temperatures are not comparable. The figures have then been plotted from 5 Km of altitude (figure 6): this is expected since the moisture becomes significant.

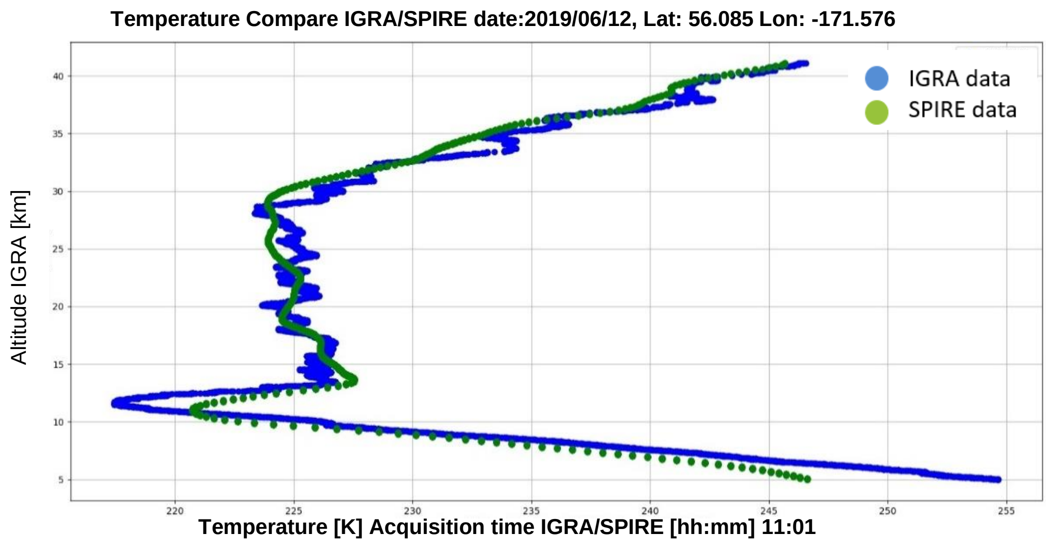



**Figure 6: SPIRE data (green / time 11:01) compared to IGRA data (blue / time 12:05)**

Since data acquisition measurement between IGRA and Spire data have been done at different altitude scale, in order to perform an intercomparison IGRA/SPIRE temperature, for each IGRA altitude and temperature measurement $h(T_{igra})$, we selected the minimum Spire altitude measurement $h(T_{spire})$ in a range of 100 metres:

$$h(T_{spire}) \leq min(h(T_{igra}) + 100)$$

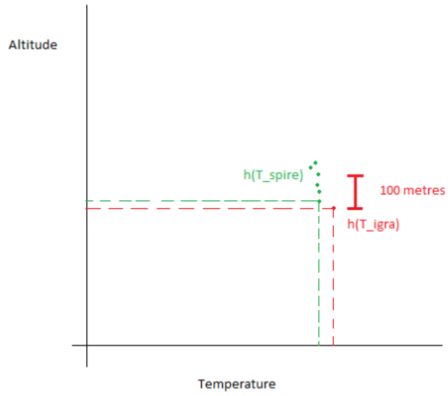



**Figure 7: shows different temperature time acquisition between IGRA (12:05) and Spire (11:01).**

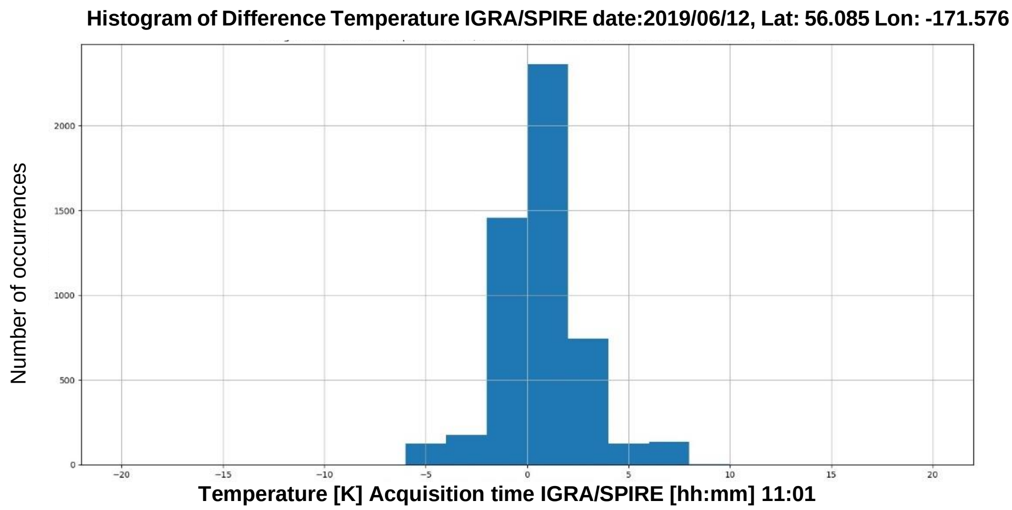



**Figure 8: Histogram difference Temperature IGRA/SPIRE**

For the same altitude has been calculate the difference between temperatures (IGRA/SPIRE) and histogram has been plotted (fig. 8). Considering the error as Gaussian, mean (dash green line) and sigma (blue dash lines) has been calculated (fig. 9).

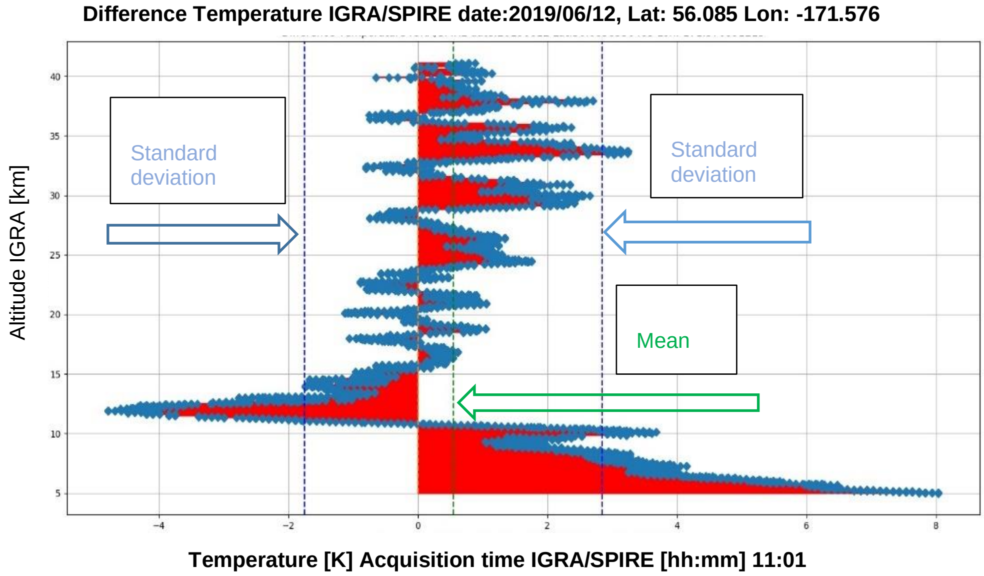



**Figure 9: Difference of Temperature for IGRA/SPIRE data (2019/06/12 Lat: 56.0858, Lon:-171.5768)**

Plot below (fig. 10) shows the comparison between IGRA/SPIRE pressures for the same IGRA station.

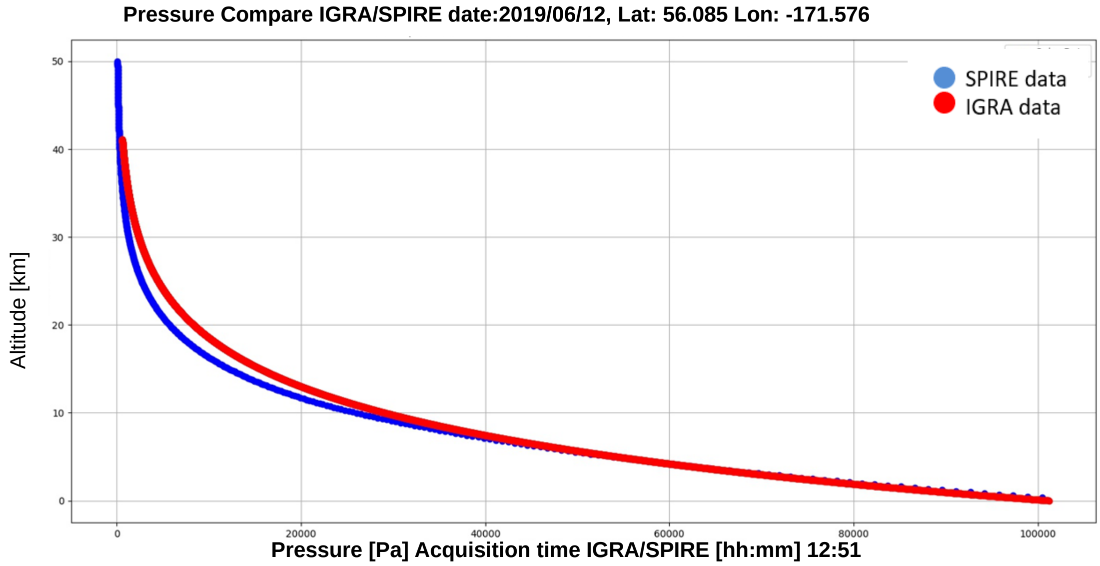



**Figure 10: IGRA/SPIRE Altitude [Km] / Pressure [Pa] (2019/06/12 Lat: 56.0858, Lon:-171.5768)**

In the next page are reported Temperature, Difference Temperature and histogram for 6 IGRA/SPIRE data.

Difference temperature plots below shows how for determinate altitude the difference of temperature is not in the range of -/+sigma.

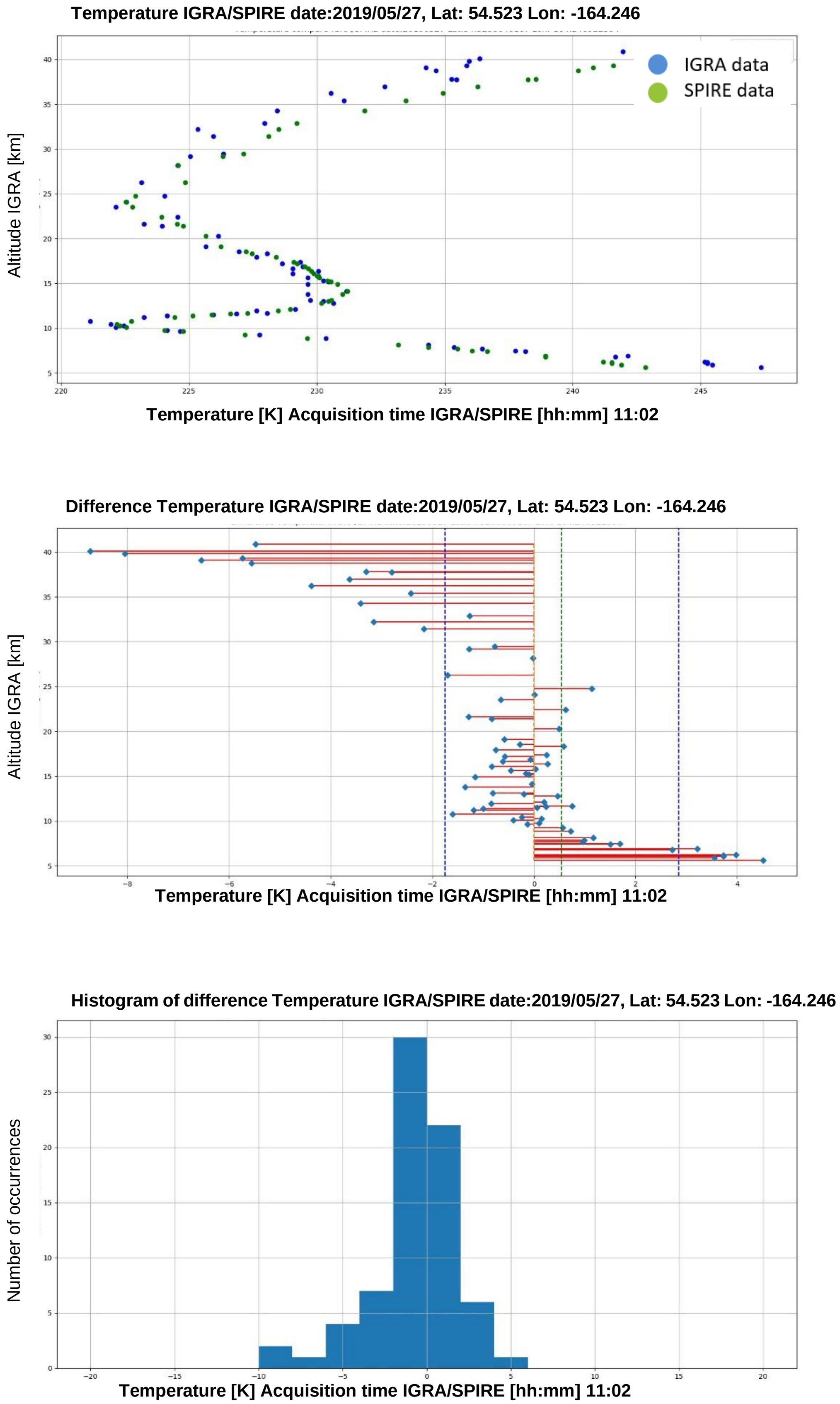
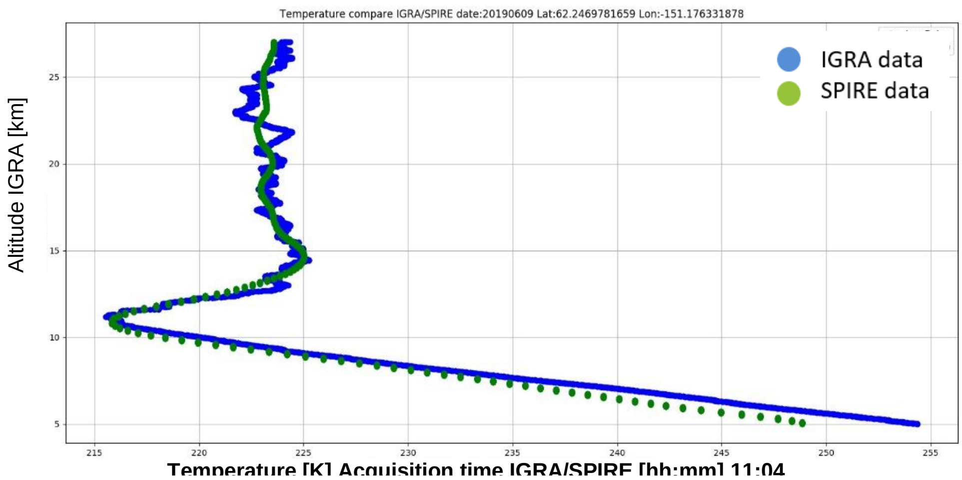
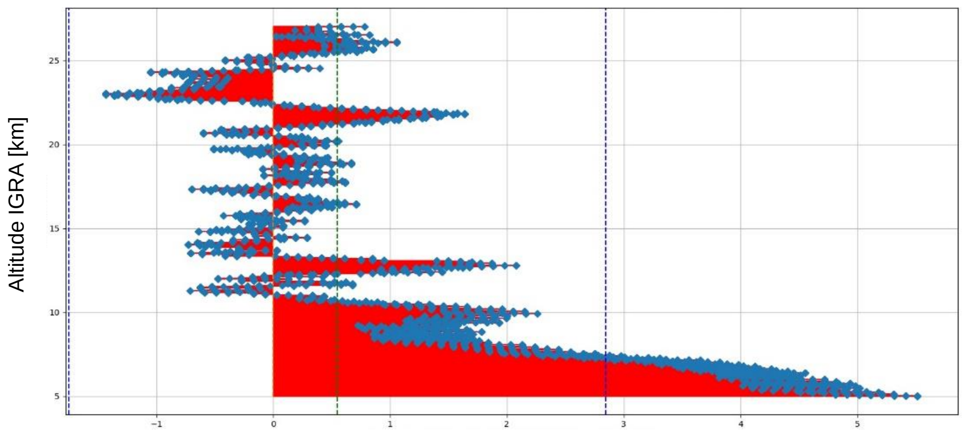



**Figure 11: Temperature, Difference Temperature and histogram for collocated point [Lat: 54.523 Lon: -164.246] IGRA/SPIRE data**

**Temperature Compare IGRA/SPIRE date:2019/06/09, Lat: 62.246 Lon: -151.176**

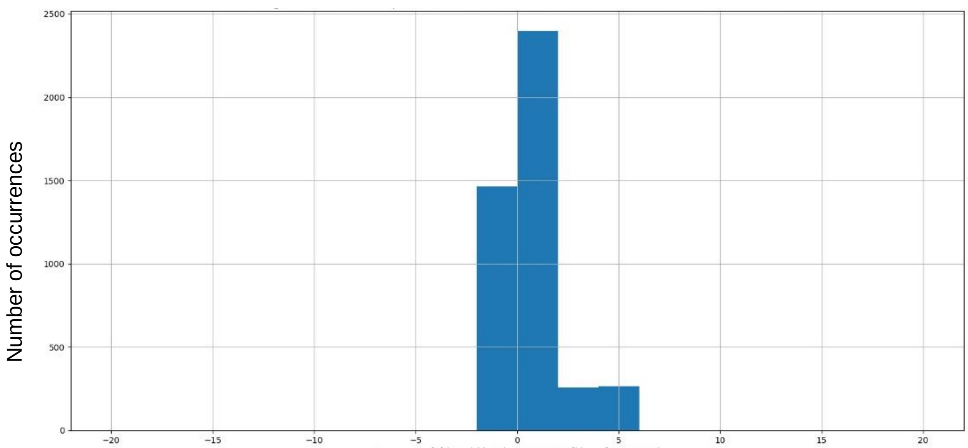



**Difference Temperature IGRA/SPIRE date:2019/06/09, Lat: 62.246 Lon: -151.176**




**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:04**

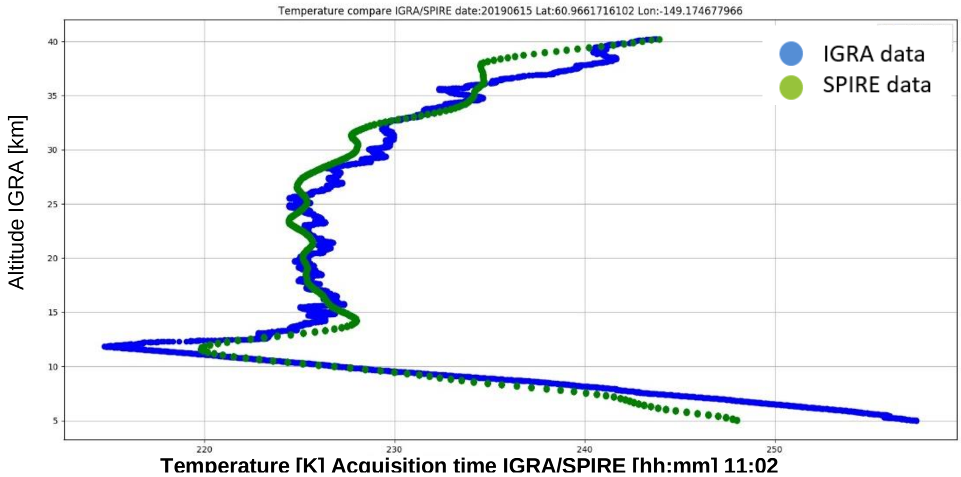
**Histogram of difference Temperature IGRA/SPIRE date:2019/06/09, Lat: 62.246 Lon: -151.176**



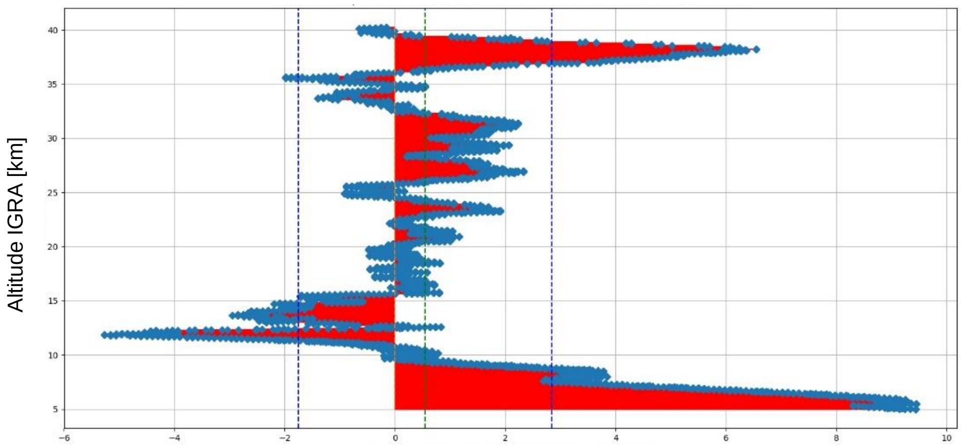

**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:04**

**Figure 12: Temperature, Difference Temperature and histogram for collocated point [ Lat: 62.246 Lon: -151.176] IGRA/SPIRE data**

**Temperature Compare IGRA/SPIRE date:2019/06/15, Lat: 60.966 Lon: -149.174**

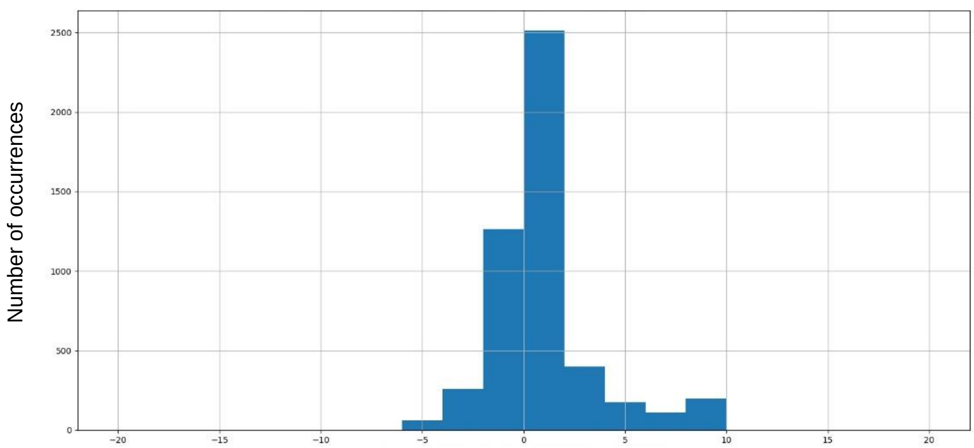



**Difference Temperature IGRA/SPIRE date:2019/06/15, Lat: 60.966 Lon: -149.174**




**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:02**

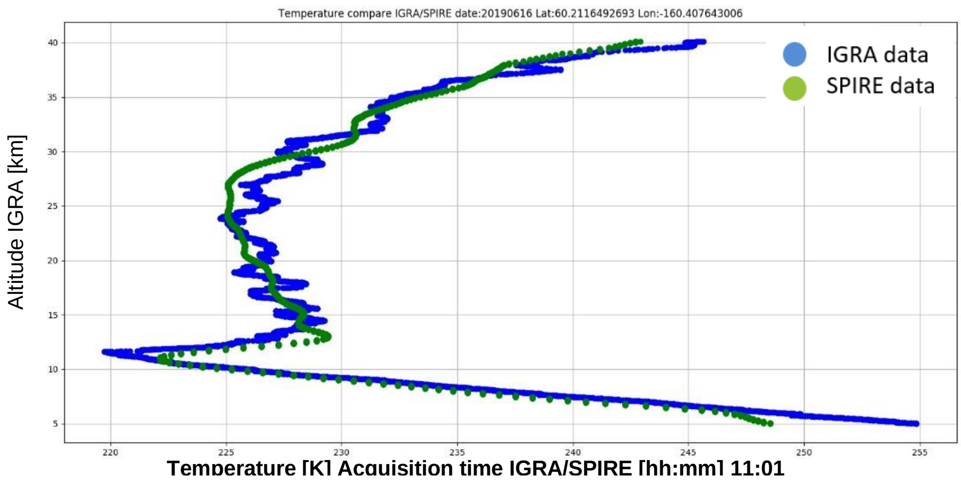
**Histogram of difference Temperature IGRA/SPIRE date:2019/06/15, Lat: 60.966 Lon: -149.174**



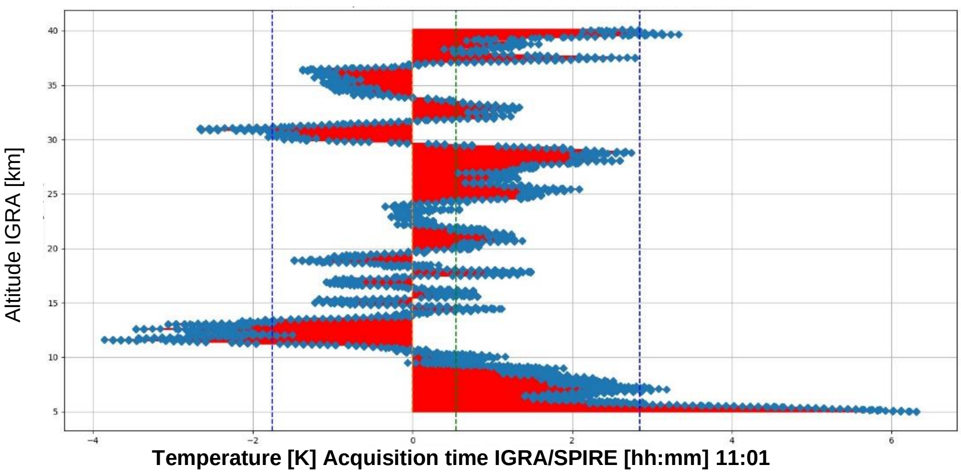

**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:02**

**Figure 13: Temperature, Difference Temperature and histogram for collocated point [Lat: 60.966 Lon: -149.174] IGRA/SPIRE data**

**Temperature Compare IGRA/SPIRE date:2019/06/16, Lat: 60.211 Lon: -160.407**




**Difference Temperature IGRA/SPIRE date:2019/06/16, Lat: 60.211 Lon: -160.407**




**Histogram of difference Temperature IGRA/SPIRE date:2019/06/16, Lat: 60.211 Lon: -160.407**

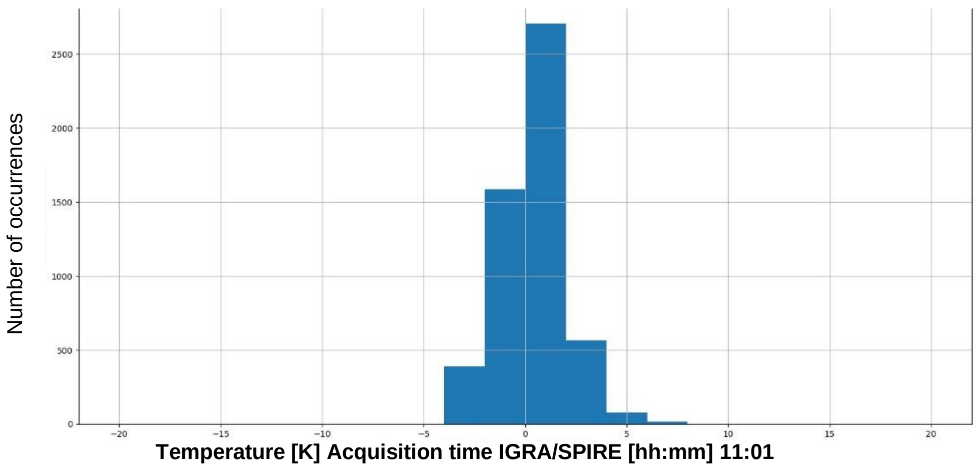
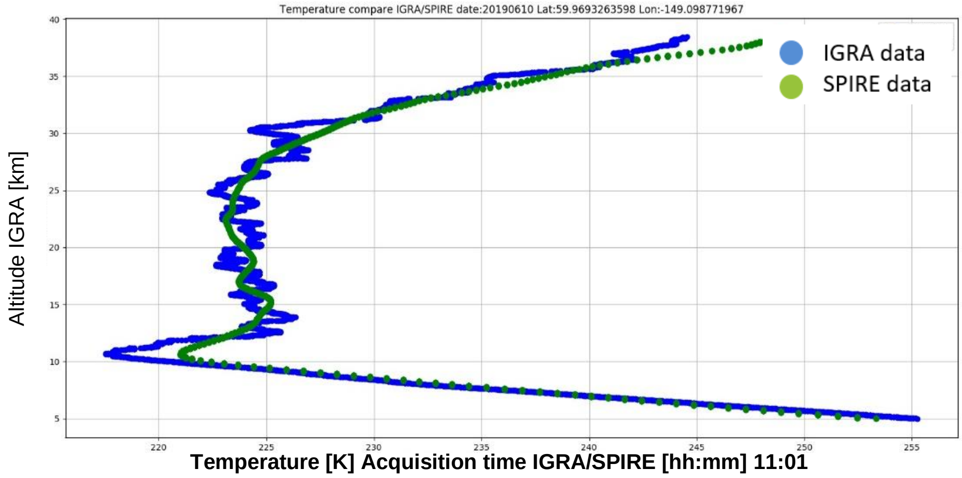
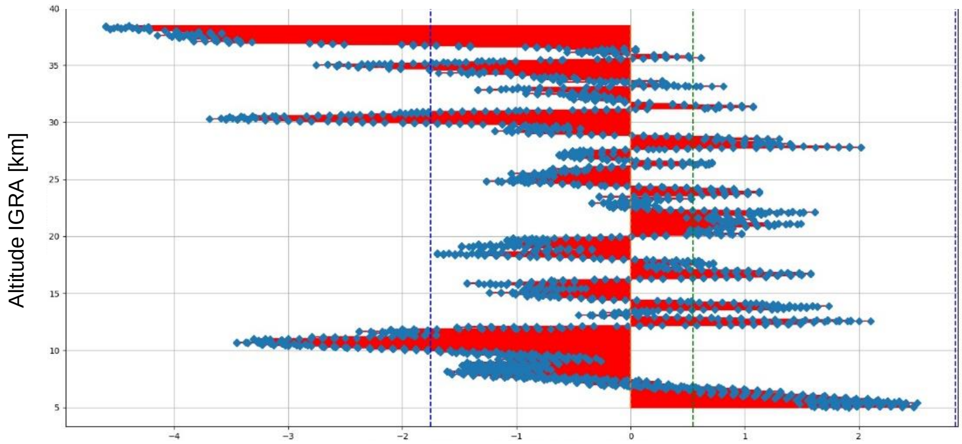



**Figure 14: Temperature, Difference Temperature and histogram for collocated point [Lat: 60.211 Lon: -160.407] IGRA/SPIRE data**

**Temperature Compare IGRA/SPIRE date:2019/06/10, Lat: 59.969 Lon: -149.098**

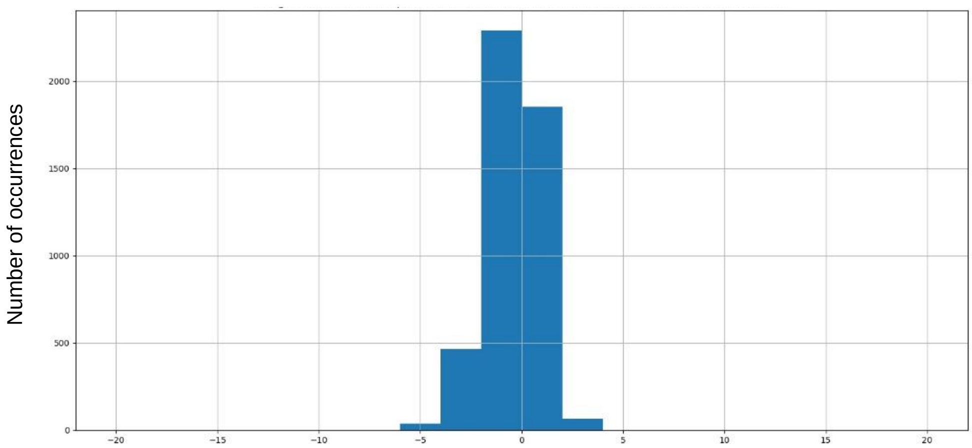



**Difference Temperature IGRA/SPIRE date:2019/06/10, Lat: 59.969 Lon: -149.098**




**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:01**

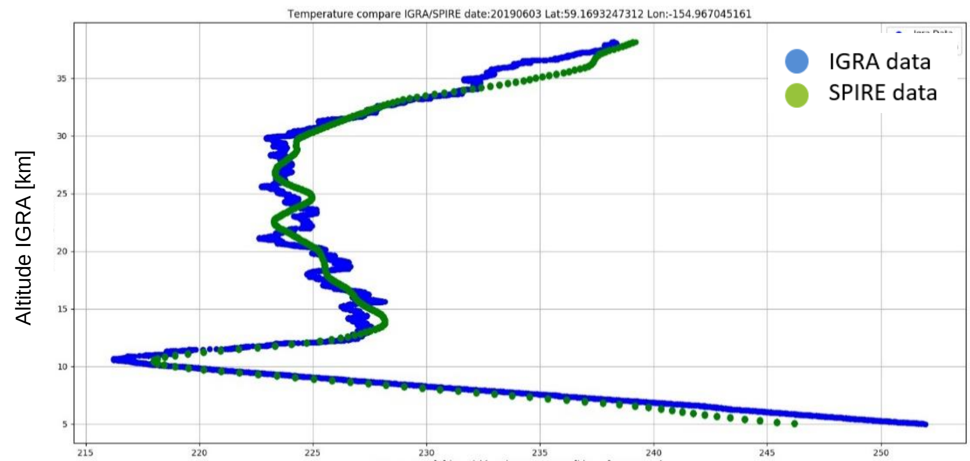
**Histogram of difference Temperature IGRA/SPIRE date:2019/06/10, Lat: 59.969 Lon: -149.098**




**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:01**

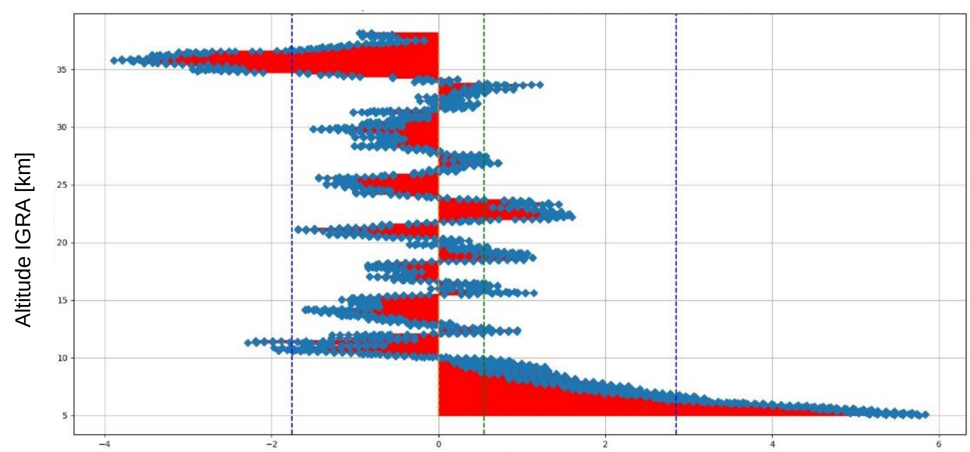
**Figure 15: Temperature, Difference Temperature and histogram for collocated point [Lat: 59.969 Lon: -149.098] IGRA/SPIRE data**

**Temperature compare IGRA/SPIRE date:2019/06/03, Lat: 59.169 Lon: -154.967**



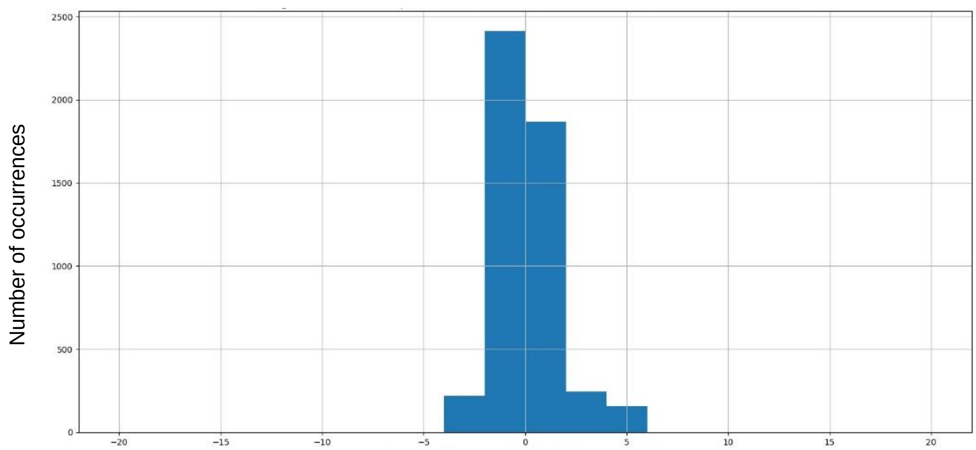

**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:01**

**Difference Temperature IGRA/SPIRE date:2019/06/03, Lat: 59.169 Lon: -154.967**




**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:01**

**Histogram of difference Temperature IGRA/SPIRE date:2019/06/03, Lat: 59.169 Lon: -154.967**




**Temperature [K] Acquisition time IGRA/SPIRE [hh:mm] 11:01**

**Figure 16: Temperature, Difference Temperature and histogram for collocated point [Lat: 59.169 Lon: -154.967] IGRA/SPIRE data**

From the above plots we can see the comparison of SPIRE data with IGRA radiosonde.

Difference of temperatures between these data in function of altitude shows how the error is in the range of the average temperature +/- the standard deviation, with some exceptions.

# 6. CONCLUSION

*In the core region (stratosphere), Spire data is highly consistent with IGRA radiosondes; the particular, this occur for specific range of altitude where data are not always comparable:*

- *0 - 5 km, in particular close to 5 km (where moisture is significant);*
- *12 - 13 Km – Tropopause;*
- *35 - 40 Km – Upper Stratosphere;*
- *A positive bias has been measured (0.5 - 1 K);*
- *In the upper troposphere to mid-stratosphere, Spire data is highly consistent;*
- *In the troposphere, measurements penetrate close to the ground, with systematic and random uncertainties;*
- *Differences between RO in the troposphere, need to be better understood.*

This is also in agreement with literature referenced.

*The deviation in Upper Stratosphere could be associated to the inversion errors associated with the observational noise.*

*The lower troposphere is important for understanding the physics of convective cloud systems, precipitation, and the hydrological cycle.*

*The deviation in tropopause are probably related to RS data have vertical resolution ranging from a few hundred metres to about a kilometre, and this is also considered as a limitation for tropopause (GNSS RO technique derives atmospheric profiles with a high vertical resolution and makes the spatial distribution of the data more homogenous).*

*The deviation in LT are fundamentally related:*

- *to moisture, that impacts the bending angle (in lower troposphere);*
- *to atmospheric propagation effects, such as the super-refraction;*
- *to contribution from the horizontal gradients of refractivity to a single bending angle.*

*In general, when there is no moisture in the atmosphere, the profiles of pressure and temperature retrieved from refractivity correspond to the real atmospheric values. But when the moisture in the atmosphere increases, the retrieval of pressure and temperature could be affected: in particular the retrieved temperature could be lower (cooler) than the real temperature of the atmosphere since the dry molecules would compensate the same refractivity produced by the real atmosphere.*

*The moisture contribution to refractivity is consistent in middle and lower troposphere: for this reason, an independent knowledge of temperature, pressure or water vapour pressure is important for the correct estimation the other two parameters. Usually:*

- *temperature is given by an external source (model) and resolved for pressure and moisture; or*
- *parameters are derived by a-priori model and optimal estimation is done.*

*Finally, Radio Occultation data are presenting many benefits:*

- *All weather-minimally affected by aerosols, clouds or precipitation;*
- *High accuracy (equivalent to ~ 0.1 Kelvin from ~7-25 km);*
- *Equivalent accuracy over ocean than over land;*
- *No instrument drift, no need for calibration;*
- *No satellite-to-satellite measurement bias;*
- *Observations can be used in numerical weather predictions without a bias correction scheme.*