Radio Occultation Webpage Development

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1. Background

Global Navigation Satellite System Radio Occultation (GNSS-RO) is a remote sensing technique that utilizes signals from GNSS satellites to probe the Earth's atmosphere. As these signals pass through the atmosphere, they are measured by low-Earth orbiting (LEO) satellites, providing high vertical resolution profiles of atmospheric parameters such as temperature, pressure, and humidity. Due to its all-weather, global coverage and fine vertical resolution, GNSS-RO is an invaluable tool for weather forecasting, climate monitoring, and ionospheric research.

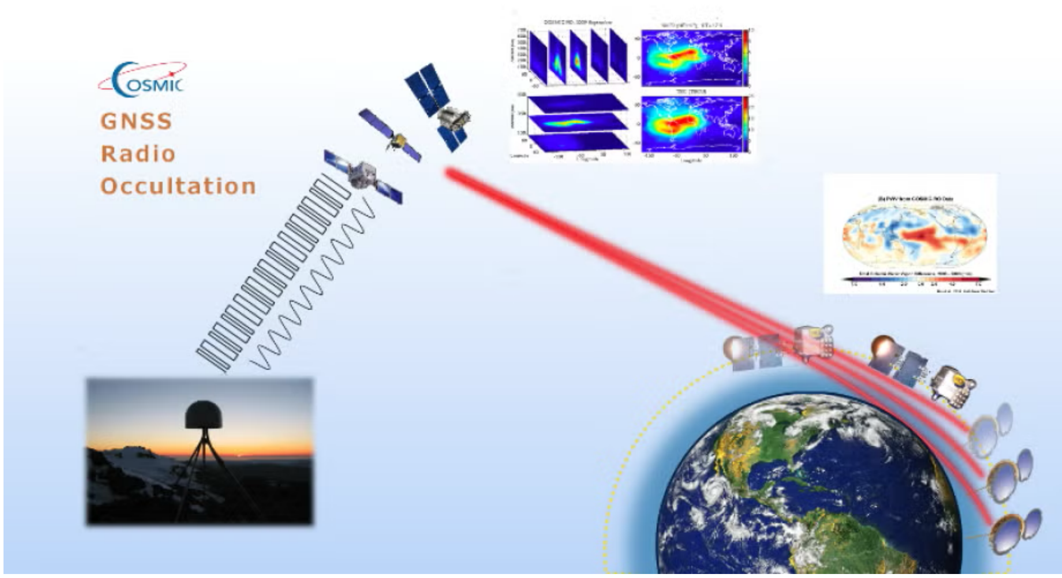

Figure 1. *Illustration of the GNSS Radio Occultation (GNSS-RO) technique. GNSS-RO is a satellite-based remote sensing method that uses signals from GNSS satellites (e.g., GPS) received by low-Earth orbiting satellites to obtain high-vertical-resolution profiles of the Earth's atmosphere and ionosphere with global coverage.*[3]

The GNSS-RO technique is illustrated in **Figure 1**. GNSS satellites determine position using trilateration, in which signals from multiple satellites are combined to derive location. Each GNSS satellite carries an atomic clock, enabling continuous transmission of its precise position in space and time. A GNSS receiver calculates its own position using signals from at least four GNSS satellites.[4]

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[2] River Hill High school, Expected graduation in 2027.
[3] "Global Navigation Satellite System (GNSS) Background."
[4] Ibid.

In GNSS-RO, these signals are observed as they pass through the atmosphere, allowing retrieval of atmospheric refractivity. The relationship between refractivity and atmospheric variables is typically described by the Smith–Weintraub equation (modified for RO applications):

$$N = 77.6\frac{p}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

where:

- N = refractivity (dimensionless, but typically expressed in N-units × 10^6)
- P = total atmospheric pressure (hPa)
- e = water vapor pressure (hPa)
- T = temperature (K)

The National Oceanic and Atmospheric Administration (NOAA) Center for Satellite Applications and Research (STAR) GNSS-RO page plays a critical role in the wider GNSS-RO data ecosystem. It is the main provider of up-to-date data to the NOAA National Centers for Environmental Prediction (NCEP) Weather Prediction Center, the Joint Center for Satellite Data Assimilation (JCSDA) (organized by NOAA, NASA, and the United States Navy and Airforce), and the European Centre for Medium-Range Weather Forecasts (ECMWF). Accordingly, the quantity of served data has increased significantly over the past year. The page is now responsible for delivering level 1b (excess phase and signal to noise ratio), level 2 (bending angle and temperature), and level 3 (monthly mean climatology) products.[5] This heightened quantity has greatly stressed internal systems. This internship has thus focused on refactoring and modernizing critical systems as well as developing new functionality to help visualize and handle the additional products.

Furthermore, a key area of concern for newly introduced functionality was to allow for efficient visualization of large quantities of GNSS-RO profiles. Such an application would greatly improve the calibration and validation processes for GNSS-RO and GNSS reflectometry, geoid undulation correction, and facilitate the investigation of physical mechanisms underlying day-night atmospheric differences. However, current monitoring tools - the NOAA GNSS-RO Ground Track Prediction webpage[6] - only provide limited, daily time-stepped figures and lack the flexibility needed. Therefore, another major focus of this internship has been to create the Ground Tracker web application, a targeted solution for the aforementioned requirements.

2. Objectives

1. Development of the Ground Tracker application. Requirements include:
    a. Web-based,
    b. Interactive 2D and 3D projections,
    c. Individual profile selection and monitoring,

[5] "STAR - GNSS Radio Occultation."
[6] "NOAA-21 Ground Track Prediction."

d. Display up to a week of GNSS profiles,
e. Color-code profiles by GNSS ID, mission, penetration depth, and signal to noise ratio,
f. Include data from the COSMIC-2, Spire, and PlanetiQ missions and the GPS, GLONASS, Galileo, and BeiDou GNSS systems.

2. Update the Integrated Calibration/Validation System (ICVS) used to monitor data quality:
    a. Ability to nest multiple charts within the same ICVS container,
    b. New page routing system to better support atmospheric profile (atmPrf) and 1D-var (1Dvar) products.
3. Data analysis of downloaded files and user base, monitoring:
    a. User location and nationality,
    b. Distribution of accessing countries and a further focus on US states,
    c. Product popularity,
    d. Downloading trends over time,
    e. Differences between downloaded file size and downloaded file count.
4. Creation of a new monthly mean humidity anomaly (MMHA) page.

3. Accomplishments

3.1 Ground Tracker Application

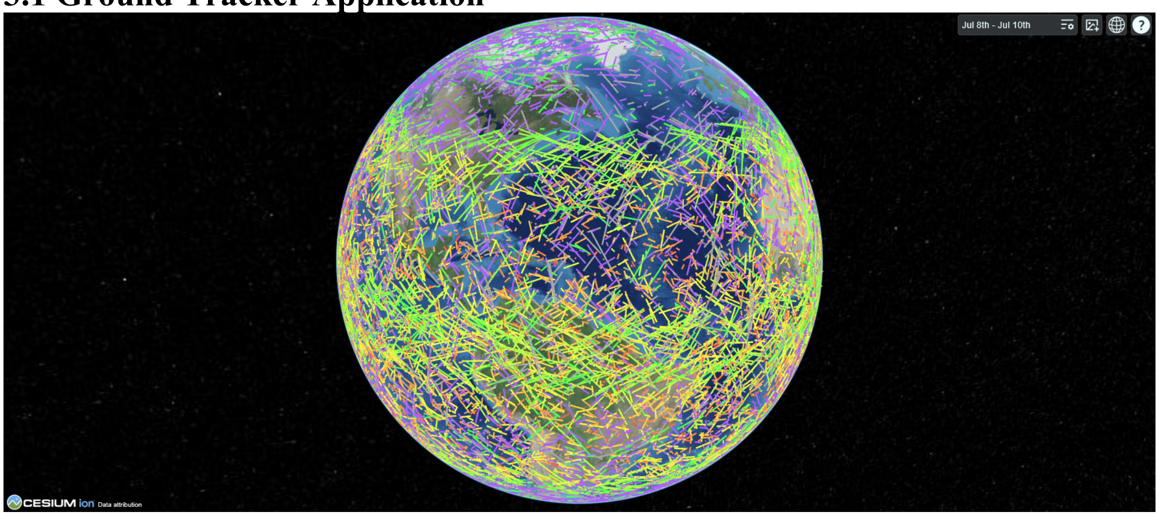

Figure 2. *_A screenshot of the Ground Tracker application, displaying 20,000 profiles from the PlanetiQ, Spire, and COSMIC-2 missions and the GPS, GLONASS, Galileo, and BeiDou GNSS systems in a 3D projection. Profiles are loaded from July 8 - 10 2025. Colors represent the signal to noise ratio; values from 0 to 2000 are colored green to red respectively. Values greater than 2000 are colored purple.*[7]

The Ground Tracker application is a web-based program for displaying and interacting with tens of thousands GNSS-RO profiles. Currently, it supports the PlanetiQ, Spire, and COSMIC-2 missions starting from June 6th, June 16th, and June 3rd 2025 respectively, and up until three days prior to the current date (as additional profiles are generated daily). The GNSS systems

[7] “Ground Tracker.”

GPS, GLONASS, Galileo, and BeiDou are additionally supported. Up to one week of profiles can be loaded at a time (50,000 profiles on average).

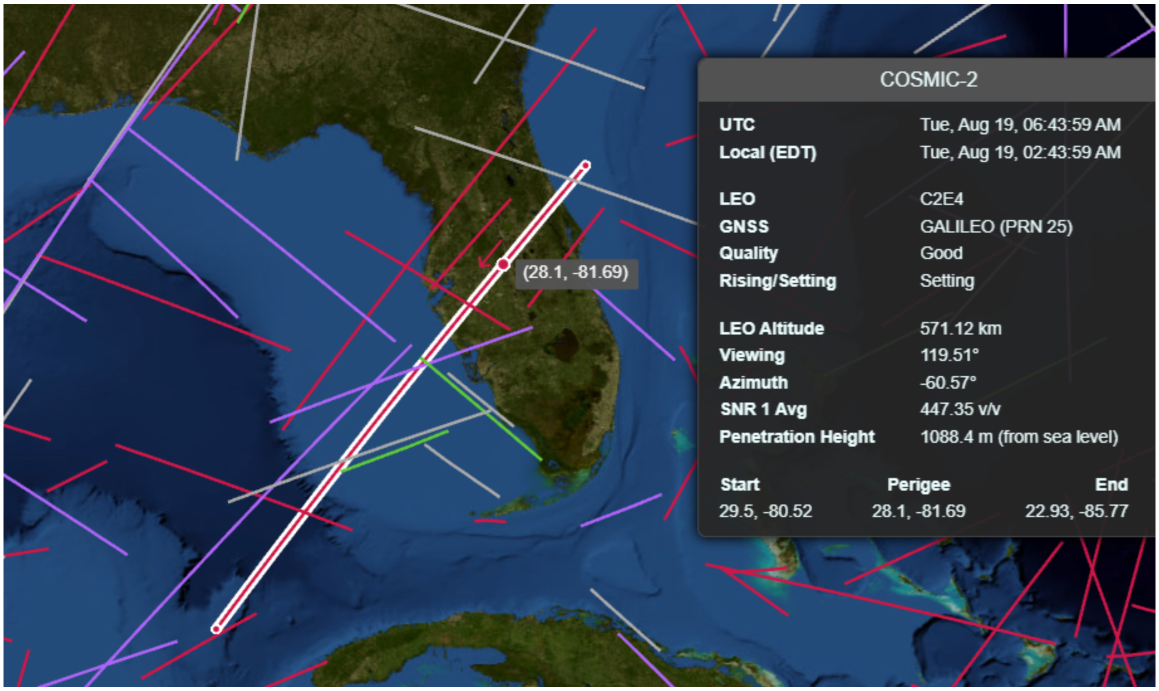

Figure 3. *An example of a selected profile, highlighted in white. Selected profiles display a side panel containing their respective information.*

Profiles are drawn as a geodesic line, defined by their starting, perigee, and ending geodetic coordinates. Users are able to select profiles via clicking their respective on-screen line, which will display a side panel with its corresponding information (**Figure 3**). Profiles can then be zoomed into via the top left magnifying glass icon in the side panel, which will move the camera closer to the profile. The perigee point will also be highlighted, with its geodetic coordinates labeled and an arrow indicating the profile's direction of movement drawn next to the point.

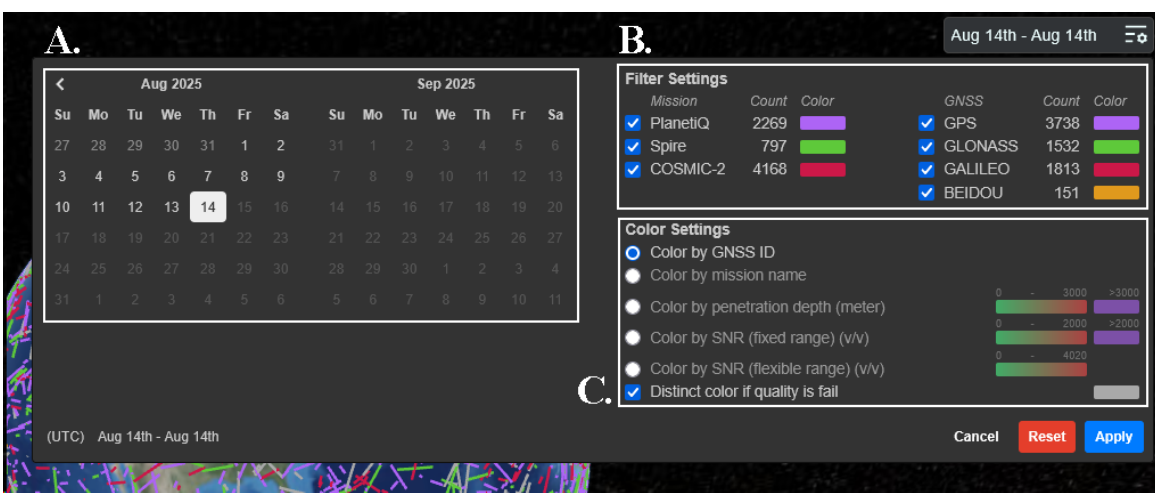

*Figure 4. The settings panel used to configure the application's parameters. **A.** The calendar input to control the date range profiles will be loaded from. **B.** The filter settings, which controls which missions/GNSS systems are loaded. **C.** The color settings, which controls how the profile lines will be colored.*

A settings panel is provided to allow the user to change the application parameters at runtime (**Figure 4**), accessible from the toolbar in the top right corner of the window (**Figure 6**). The left-hand side displays the calendar input (**Figure 4.A**), which specifies the time range profiles should be loaded from. As mentioned previously, up to a week can be selected at once. In the top-right are the filter settings (**Figure 4.B**). This controls which missions and GNSS systems are displayed. Additionally shown is the count of currently enabled missions/GNSS systems and their respective colors. Note that this color is only used if the "Color by GNSS ID" or "Color by mission name" option is selected in the color settings sub-panel. The color settings panel is in the bottom right (**Figure 4.C**), and specifies how the profiles will be colored in the application. Five mutually exclusive options are provided: coloring by GNSS ID or mission name, coloring by penetration depth (with scale 0 - 5000 meters, green to red, and values greater than 5000 in purple), and coloring by signal-to-noise ratio (SNR). For coloring by SNR, this is divided into a fixed or flexible range option. Fixed range colors all profiles with SNR values from 0 to 2000 as green to red, and values greater than 2000 as purple. Flexible range colors profiles by the range of SNR values of the currently loaded profiles, from green to red as well. Lastly, a toggle is provided to control if profiles with a quality parameter equal to "Fail" are colored as gray.

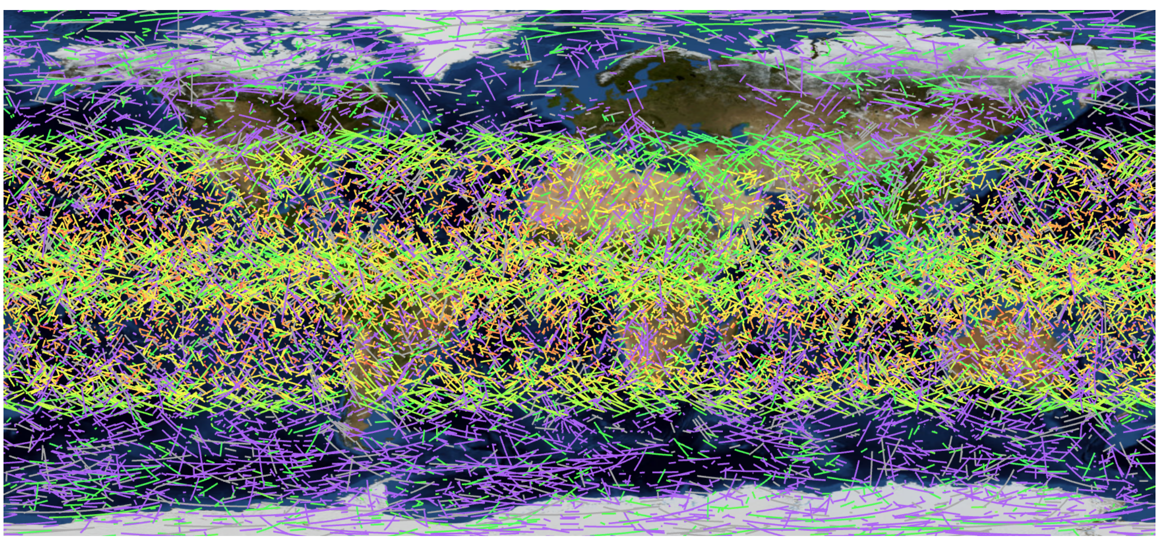

***Figure 5.** The 2D projection view, using the same parameters as defined in **Figure 2**. This image was taken using the built-in screenshot functionality.*

Finally, the application supports both a 3D and 2D projection of the environment (**Figure 5**), which can be switched between freely. All application functionality is retained in both projections.

***Figure 6.** The toolbar, positioned in the top-right corner of the application. From left to right, these buttons are: the control panel, screenshotter, projection controller, and help menu.*

Outside the core set of defined requirements, a permalink system, automatic screenshotter, and help menu were implemented. The permalink system writes the current projection mode, camera position, control panel settings, time range, and selected profile (if any) to a URL. Upon loading the URL, all aforementioned parameters are automatically set to their defined values and the application loads profiles as appropriate. If a user accesses the application without a permalink, then a welcome screen is shown to configure the initial scenario.

The screenshot system can be accessed in the toolbar (**Figure 6**). It will automatically download an image of the current viewport (in PNG or JPEG format) without the application UI. However, note that the UI associated with profile selection will be retained (**Figure 3**).

The help menu is also accessible through the toolbar (**Figure 6**). It shows the mouse and touch controls used to control the camera. It also defines some of the variables used inside the side panel (**Figure 3**) shown on profile selection: azimuth angle, viewing angle, SNR 1 average, and penetration depth.

3.2 ICVS Monitor Webpage Updates for GNSSRO Level 2 Products

Figure 7. The new multi-chart functionality introduced. Multiple charts, with individual zoom controls, can be nested together inside the same chart container.[8]

The two notable changes to the ICVS pages were the introduction of a multi-chart functionality (**Figure 7**) and modernization of how the pages are served to the user. The multi-charts allow users to view related variables without needing to switch between tabs; this makes the view more compact and user friendly. Internally, this required the additional implementation of an improved

[8] "COSMIC-2."

chart lifetime tracking system and rewriting the zoom functionality as a reusable object so that it can be attached to multiple charts.

The second major change was modernizing the page routing system. Previously, each mission and variable required a separate, unique page despite their large degree of similarity. Furthermore, pages had to be accessed via a full link to the exact version of each file. In the new system, URLs have been simplified to just the variable and mission name and are independent of version. For example, cosmic2_star_v2.38_l2a.php has been moved to atmPrf/cosmic2 and spire_1dvar_v3.2_l2b.php has been moved to 1dvar/spire. This also greatly increases maintainability and reduces code duplication as internally all pages are represented by the same template file. Two config files (one for the atmospheric profile and 1D-var variables each) read their respective URLs and automatically retrieve the needed data. This information is then passed to the template file, which generates the page for the user.

3.3 Download Data Analysis

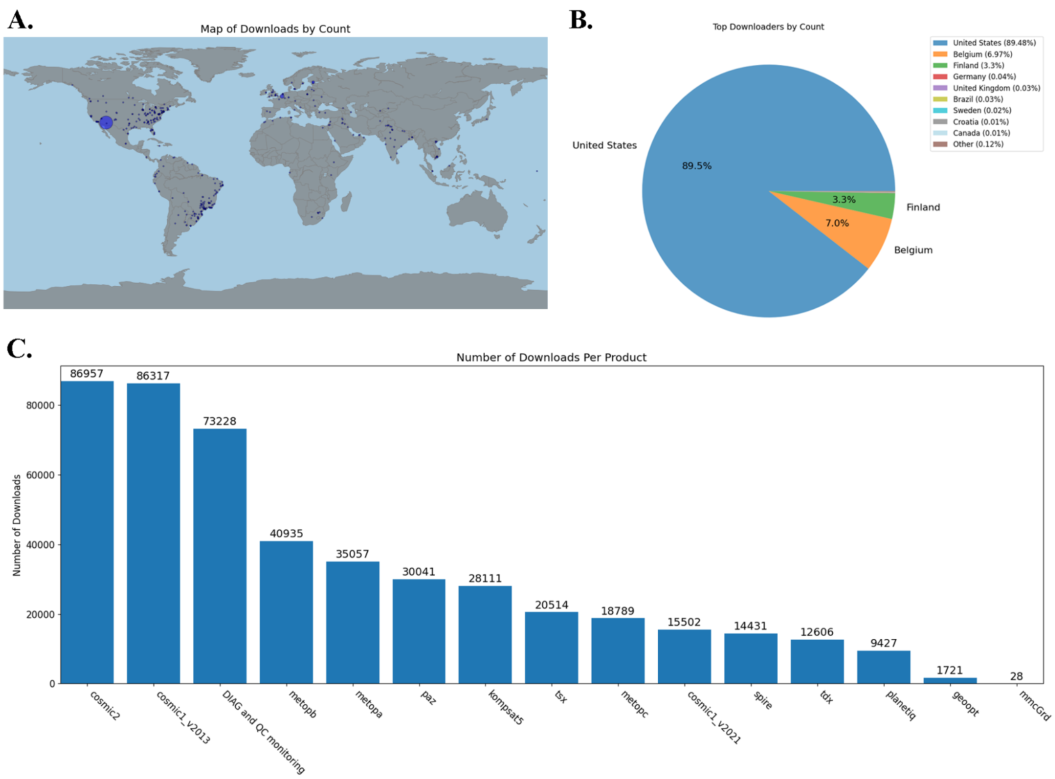

Figure 8. *A selection of figures generated from the download activity of the HTTP and FTP servers from June 1st 2025 to August 14th 2025.* ***A.*** *A map of the location of each unique user (as determined by IP address). A larger radius indicates a greater number of files downloaded.* ***B.*** *A pie chart of the top-10 countries by download count.* ***C.*** *A bar chart of the total number of downloads for each product.*[9]

The NOAA STAR GNSS-RO page's role as a data provider necessitated an understanding of how users were interacting and downloading products. To this end, a custom python tool was built to analyze the HTTP and FTP logs. Over the June 1st to August 14th 2025 period, it recorded

[9] "RO SDC Data Downloads."

473,000 file downloads from 1772 unique users, transferring a total of 74.86 TB. The program also generated a map of user locations (**Figure 8.A**), pie charts of the top-10 downloading countries (**Figure 8.B**), top-10 downloading states in the US, and top-10 downloading countries excluding the US. Additional charts include the total number of downloads per product (**Figure 8.C**), downloads over time, and cumulative downloads. Finally, all charts except for the pie charts include two versions, one for downloads by file size and another for downloads by file count. These statistics are automatically updated and published daily.

3.4. Webpage Design for GNSSRO Level 3 products

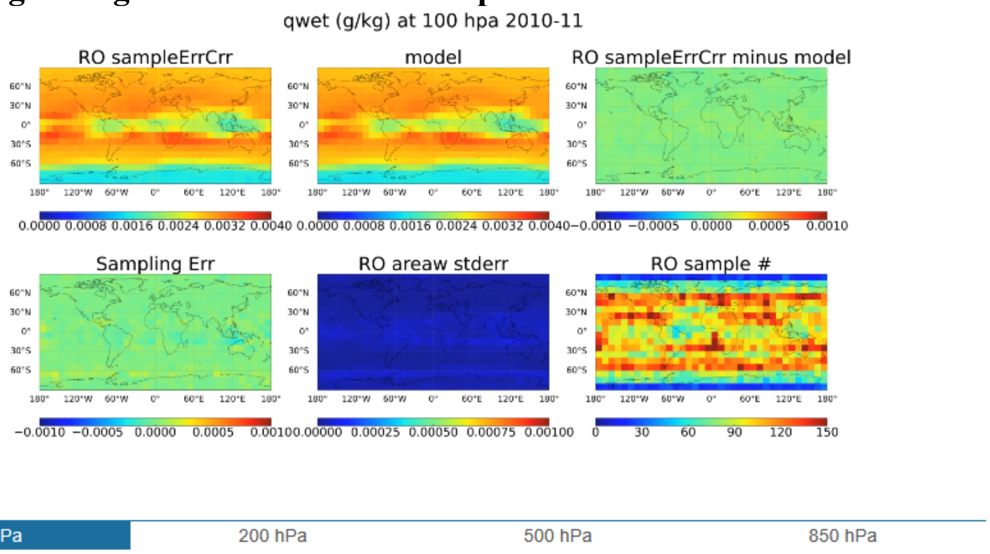

Figure 9. *Embedded graphs within the MMHA page, displaying the provided product at 100, 200, 500, and 850 hPa from 2002 to 2014.*[10]

The monthly mean humidity anomaly page (MMHA) page was created to host the recently added level 3 products in 5^{O} degree by 5^{O} degree, as well as the data definition. It also includes a video of the data file at each offered pressure level (100, 200, 500, and 850 hPa) across the available time range (2002 to 2014).

4. Conclusion

Our internship has accomplished, and in areas, exceeded the requirements initially set out. We have been able to modernize key areas of the STAR GNSS-RO website, gain a more complete understanding of our users, and implement new functionalities. The updated page routing for the ICVS pages simplifies the user experience through the new consistent set of URLs and increases code maintainability through the introduction of a template and config file system. Next, the data analysis done on downloaded products provides better insight on the makeup of our users (including country/US state) and thus how to best serve them. Finally, the new Ground Tracker application enhances data accessibility, improves visual interpretation of satellite orbits and occultation profiles, and supports NOAA's ongoing efforts in atmospheric monitoring and research.

[10] "Monthly Mean Humidity Anomaly."

Moving forwards, there are still a number of improvements that could be implemented. For the download data analysis, although we can locate the geographical position of users, we are unable to identify their parent organization or what the data is used for. Migrating to a new IP identification service or a creation of a look-up table (for known IPs) could be used to aid in this functionality. The tool additionally parses through all download logs every time it is run, which can incur a serious time cost as the number of logs is constantly growing. The introduction of a caching system where the processed results of old logs are saved (such that only newly added logs need to be processed) could massively speed up the program.

For the Ground Tracker application, extending it to include additional missions or GNSS systems (or even a system where arbitrary missions/GNSS systems can be included) is an obvious next step. Similarly, allowing users to create custom filters or color settings would greatly increase the program capabilities. Finally, there is still room for general performance optimizations. This includes fixing a rare issue with the Javascript garbage collector, where the program may freeze for a couple of seconds after unloading a large amount of profiles. Furthermore, load times could be decreased by optimizing how Cesium entities are created by reducing the byte size/stored data in each entity.

5. Acknowledgements

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5. References

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