METHODOLOGY FOR THE VALIDATION OF TEMPERATURE PROFILE ENVIRONMENTAL DATA RECORDS (EDRS) FROM THE CROSS-TRACK INFRARED MICROWAVE SOUNDING SUITE (CRIMSS): EXPERIENCE WITH GPS RADIO OCCULTATION FROM COSMIC

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1. INTRODUCTION

Atmospheric temperature is an important input to numerical weather prediction (NWP) models used to provide daily global weather forecasts. Traditionally the temperature profile used in NWP data assimilation has come from the global WMO network of radiosonde launch sites. The distribution of these sites is biased toward land areas and concentrated mainly in developed countries like the continental United States and Europe. Since the 1970's the use of satellites to provide temperature information on the atmosphere has taken on increasing importance. Microwave sounders in particular have been successfully integrated into operational weather forecast data assimilation system (Healy and Eyre 2000). The infrared sensors on the NOAA series of satellites, ATOVS, have also been assimilated with an emphasis on observed channels that peak high above the surface and clouds (Borbas et al. 2003). This paper presents a methodology for validating the measurements from the advanced high-spectral resolution infrared Cross-track Infrared Sounder (CrIS) on the NPP satellite, the first satellite of the newly created U.S. JPSS program. In particular, the temperature profiles from the Cross-Track Infrared Microwave Sounding Suite (CrIMSS) will be compared against special launches of Vaisala radiosondes at three climate sites operated by the Department of Energy Atmospheric Radiation Measurement (ARM) program. The validation of air temperature vertical profiles, a key NPP Environmental Data Record (EDR), against research grade radiosondes will follow Tobin et al. 2006. This paper will describe an additional methodology for validation that makes use of temperature profiles obtained from radio occultation between GPS satellites and satellite-based receivers. In particular, experience of performing matchups between GPS temperature profiles from the COSMIC project and NASA AIRS L2 version 5 products will be presented as a proxy for the same comparison expected with CrIMSS EDRs. The unique issues of time and space matchups between the GPS occultation profiles (pseudo-random in space and time) with satellite and ground sites will be described and a preliminary assessment of product accuracies presented.

2. DATA

COSMIC data was obtained from the COSMIC Data Analysis and Archival Center-CDAAC (http://cosmic-io.cosmic.ucar.edu/cdaac/products.html). The product used was COSMIC version 2010.2640 named 'atmPrf'. A typical COSMIC profile is obtained in about 100 seconds with over 3,000 vertical samples. The netcdf files contain time in units of GPS seconds, which are 15 seconds ahead of UTC. The netcdf files also contain azimuth angle of the occultation plane at tangent point with respect North direction, positive to the East from the North direction. The angle is measured between North and the GPS direction of the ray path. A quality control flag is included in the GPS RO netcdf files. For an example day, 19 October 2007, the percentage of GPS profiles marked bad was 2.5%. These bad profiles are excluded from the analysis.

AIRS data was obtained from the Goddard Earth Sciences Data and Information Services Center (http://disc.sci.gsfc.nasa.gov/AIRS/data-holdings/by-data-product/data_products.shtml). The product used was Level 2 version 5 AIRX2SUP. An AIRS granule contains about 6 minutes of data, i.e. 135 scan lines of L1B or 45 scan lines of L2. A latitude-longitude bounding box for each AIRS granule was extracted from the XML files obtained from the Goddard data archive. The nominal size of an AIRS L2 retrieval field of view is 45 km (3x3 L1B). The AIRS L2 data file contains a quality flag, PBest, which was used to exclude profile levels with pressure greater than PBest.

ARM data was retrieved through the DOE ARM data archive (http://www.archive.arm.gov/arm login/login.jsp). The Vaisala-processed profiling data from balloon-borne sounding systems was used from the Tropical Western Pacific sites (twpsondewnpn).

3. METHODOLOGY

Spatial matchups were obtained between each COSMIC RO profile and corresponding AIRS granules for a complete day. The matchups used in this study have the COSMIC RO profile occurrence within one hour of the beginning of the corresponding AIRS granule. The latitude and longitude of the perigee at the occultation point of the COSMIC profile was collocated within the bounding box of the AIRS granule. Figure 1 illustrates the COSMIC/AIRS matchups for one day. The ratio of the number of matchups to the total number of RO profiles on 19 October 2007 was 217/1116 or 6.6%. Table 1 shows the dependence of the COSMIC/AIRS matchup yield on the time difference cutoff setting. Increasing the matchup time difference to 1.5 hours only increases the yield to 10 percent. The azimuth angle (from North) of the radio occultation for each COSMIC RO profile altitude was used to compute the spatial extent of the horizontal resolution (150 – 300 km). Figure 2 shows the horizontal resolution of the COSMIC RO profile overlaid on a map of the AIRS fields of view. Figure 3 illustrates an example where the bounding volume is not rectangular. Figure 4 illustrates the horizontal extent of a typical GPS RO profile retrieval as a 3D plot. Figure 5 shows a sample comparison of an AIRS L2 temperature retrieval and a coincident COSMIC GPS RO profile. Note the higher vertical structure apparent in the GPS profile, however the deviation for altitudes below 500 mb is due to contamination of the RO profile from water vapor (Kursinski et al. 1997, Anthes et al. 2008).

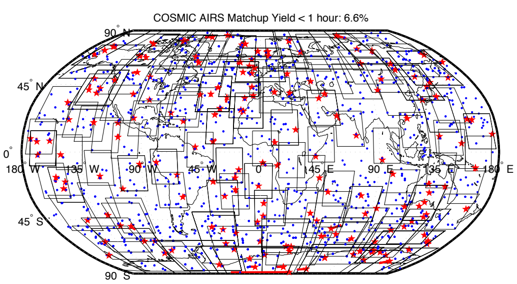


Figure 1. Locations of COSMIC RO profiles (blue dots) and AIRS granule bounding boxes (black squares) with COSMIC RO matchups within one hour (red stars) for 19 October 2007.

Time Difference Cutoff (Hours)	Matchup Number	Percent Yield (%)
0.5	147	4.5
1.0	271	6.6
1.5	316	9.7
2.0	437	13
2.5	530	16
3.0	644	20

Table 1. COSMIC/AIRS Matchup Yield

As a preliminary approach in our matchup analysis, the AIRS fields of view within a circle of radius 150 km centered at the latitude/longitude of the perigee of the COSMIC RO profile were found. To investigate the effect of the horizontal resolution of the COSMIC RO profiles, the average AIRS profile within 150 km was compared with the closest AIRS profile. Figure 6 shows a comparison of the closest AIRS profile to the area average AIRS profile and to a coincident COSMIC RO profile.

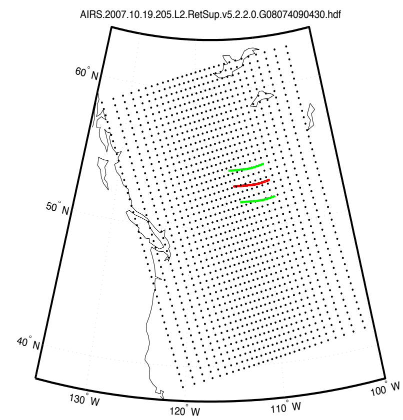


Figure 2. COSMIC RO profile (red line) with horizontal resolution (green lines) overlaid on AIRS fields of view (black dots).

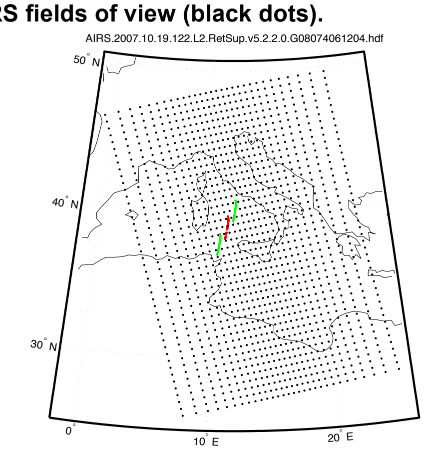


Figure 3. COSMIC RO profile (red line) and AIRS fields of view (black dots) showing the effect of RO azimuth angle on COSMIC profile bounding volume.

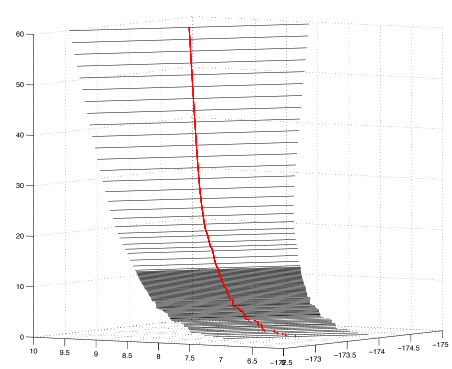


Figure 4. Example COSMIC RO profile (red dots) with horizontal averaging rays (black lines shown for every 50 levels).

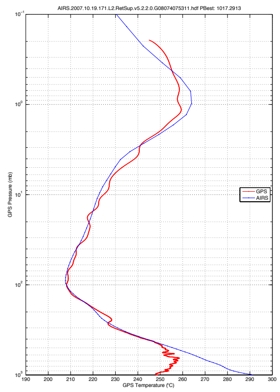


Figure 5. Example comparison of COSMIC GPS RO profile and matched AIRS L2 retrieval for 19 October 2007 at about 17:10 UTC.

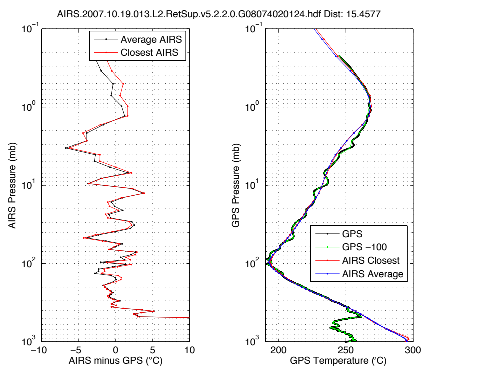


Figure 6. Comparison of a COSMIC RO temperature profile to spatially weighted AIRS profile (Weighted) and the closest AIRS profile (Closest); overlaid (right) and as a difference profile (left) from 19 October 2007 at about 01:20 UTC.

Statistical analysis was performed on zonal matchup sets to compute mean bias and root mean square (RMS) for the Focus Day. To facilitate this comparison, the COSMIC RO profile was interpolated to the pressure levels of the AIRS Level 2 support product. Figure 6 illustrates the difference profile between COSMIC and AIRS at the AIRS 100 pressure levels. For consistency with the analysis of Tobin et al. (2006), we degrade the difference profiles to approximately 1 km layers as a final step in the COSMIC and AIRS comparison. Bins are roughly 1km up to ~100 mbar and then get larger; the last bin is ~40 km high.

The CrIMSS EDR product requirements are defined for 1 km layers from the surface to 300 mb, 3 km layers from 300 to 30 mb, and 5 km layers from 30 mb to 0.5 mb. The RMS error requirement ranges from 1.5 K to 3.5 K over this altitude range.

An additional reference for comparison of temperature profiles was introduced with ARM radiosonde measurements from selected Tropical Western Pacific (TWP) sites. Due to the low matchup occurrence between the three methods, a looser temporal restriction was applied with the greatest time lapse being just over three hours; however, both the GPS RO and radiosonde profiles were still confined within the spatial extent of the AIRS granule. Examples illustrating the profile comparison in the tropopause region are included in the results section.

4. RESULTS

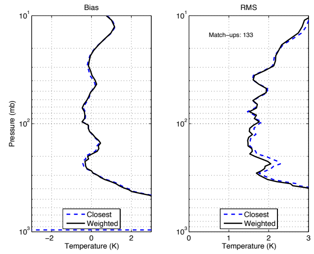
Following Yunck et al. 2009, we computed the bias and RMS statistics of the COSMIC/AIRS matchups for Arctic, Northern Mid-Latitude, Tropical, Southern Mid-Latitude, and Antarctic zones. Figures 7 and 8 show the results for these latitude zones on the CrIMSS Focus Day 19 October 2007 along with global statistics. Figure 7 illustrates the bias and RMS profiles on the AIRS 100 pressure levels while Figure 8 contains the same matchup cases degraded to 1 km vertical resolution. Shown on each figure are both the statistics of the closest profile to AIRS (solid line) and the spatially weighted average AIRS profile (dashed line).

Inspection of Figure 7 and 8 show that the spatially weighted AIRS profile has a lower RMS error for all latitude zones and all altitudes. The magnitude of the reduction in error is small but significant at some levels. Proper use of the azimuth angle of the occultation ray of the GPS signal in matchups with CrIMSS products may prove to be important.

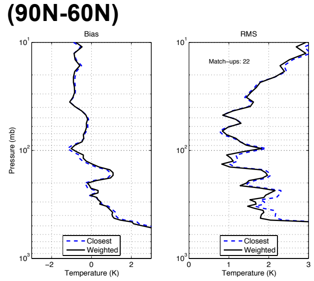
The vertical averaging of the AIRS minus COSMIC differences shown in Figure 8 is effective in reducing both the overall RMS error and the smoothness of the RMS profile in the vertical. However, the profile shape of the bias and RMS profiles is largely preserved.

Comparison of the results for tropics and higher latitudes indicates that the water vapor contamination of the GPS retrieved temperature profile varies with the height of the moist troposphere. Both the bias and RMS error increases rapidly at a characteristic pressure that varies with latitude zone; 400 mb (tropics), 500 mb (Arctic), and 600 mb (Antarctic). In general, the AIRS minus COSMIC RMS is between 1 and 2 degrees for the pressure range 30 mb to 300 mb. We expect CrIMSS products, when they become available, to achieve a similar degree of accuracy.

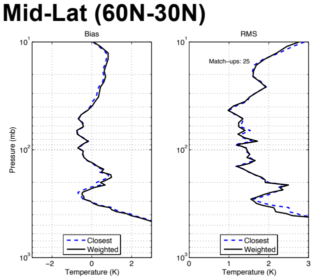
(a) Global



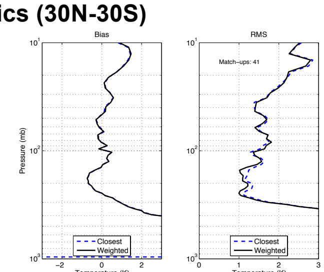
(b) Arctic (90N-60N)



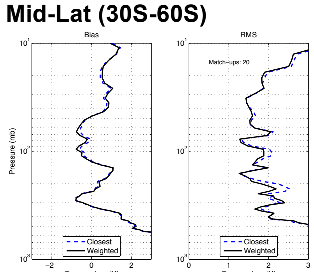
(c) North Mid-Lat (60N-30N)



(d) Tropics (30N-30S)



(e) South Mid-Lat (30S-60S)



(f) Antarctica (60S-90S)

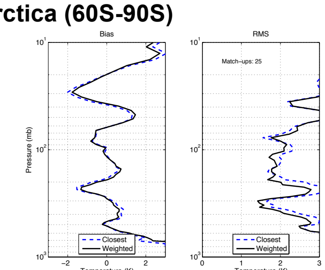
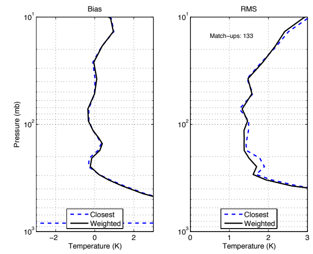
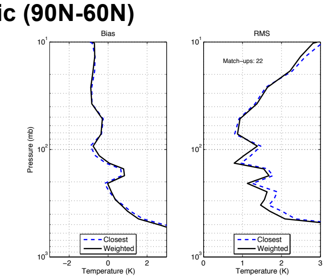


Figure 7. AIRS 100 Levels

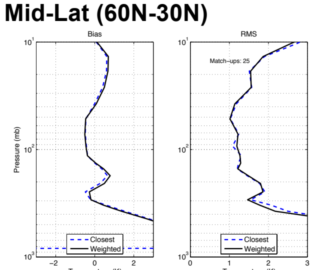
(a) Global



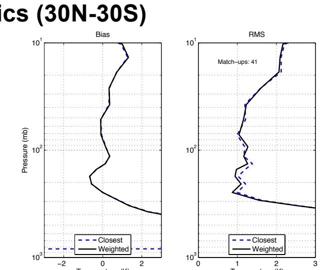
(b) Arctic (90N-60N)



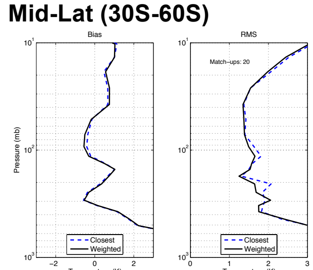
(c) North Mid-Lat (60N-30N)



(d) Tropics (30N-30S)



(e) South Mid-Lat (30S-60S)



(f) Antarctica (60S-90S)

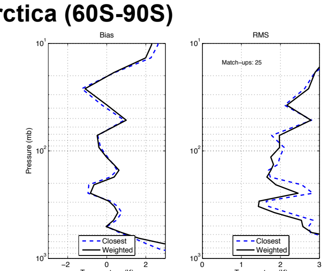


Figure 8. 1 km Layers

Figure 9 summarizes the AIRS minus COSMIC RMS statistics versus latitude for the CrIMSS Focus Day. The increased error in the COSMIC profile due to water vapor contamination in the mid-troposphere is seen in the latitude dependence of the RMS error. In general, error in the 400 mb level increases from pole to equator. The RMS error between 30 mb and 300 mb is nearly constant, independent of latitude. The latitude dependence of the bias error follows a similar pattern to the RMS error with nearly constant bias for the altitude range between 30 mb and 300 mb. The lower panel of Figure 9 shows the number of matchup samples passing quality control in each latitude bin. The number of samples per latitude bin for a single day is relatively small but adequate for this Focus Day. The latitude sampling of the COSMIC data is known to vary with season. For example, the month of January 2007 has very few matchups (within one hour) in the tropical region, all of the matchups are at high latitudes. This is believed to be a consequence of the GPS satellite radio occultation having a seasonal dependence with respect to the local time of the sun synchronous Aqua satellite.

Further characteristics of the GPS RO and AIRS profiles can be seen when overlaid with radiosonde temperature profiles as in Figures 10 and 11. The NOAA NPROVS system was used to select two matchup examples with radiosonde launches from the ARM TWP Nauru Island site. The number of three way mathups is very limited in number so the results are somewhat qualitative in nature. In general, below the tropopause level, the three profiles are in good agreement. Figure 10 shows 1) above 30 mb altitude the AIRS retrieved profile is much smoother than the GPS profile, 2) AIRS, GPS, and radiosonde profiles agree reasonably well in the 300 mb to 30 mb altitude range, and 3) below 300 mb the AIRS and radisonde are in good agreement while the GPS profile is in error. The close up view of the tropopause region is shown in Figure 11. The GPS RO's closer tracking of the radiosonde's temperature fluctuations above the tropopause suggests greater vertical resolution in the GPS data than the AIRS profile in the lower stratosphere. The cases shown in Figure 11 also illustrate the AIRS ability to retrieve the temperature at the tropopause height. The lower panel of Figure 11 shows an example where the AIRS retrieval agrees with both GPS and radiosonde. The upper panel shows an example where the AIRS retrieval smooths through the narrow tropopause features leading to a warm bias error.

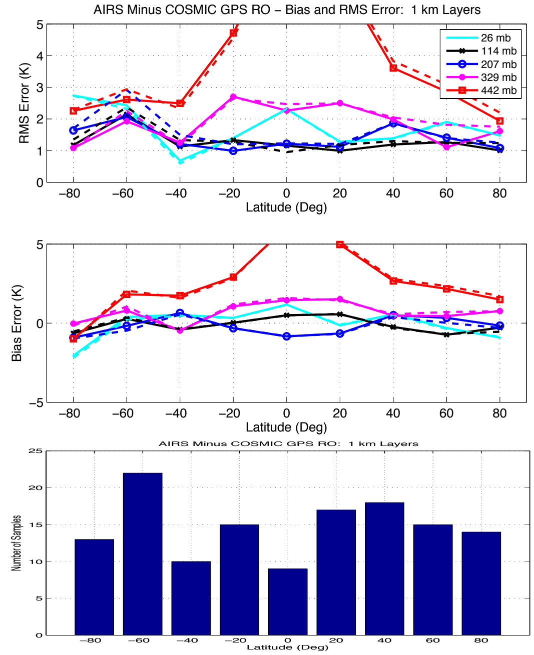


Figure 9. AIRS minus COSMIC RMS statistics versus latitude for 20 degree latitude zones for Focus Day 19 October 2007.

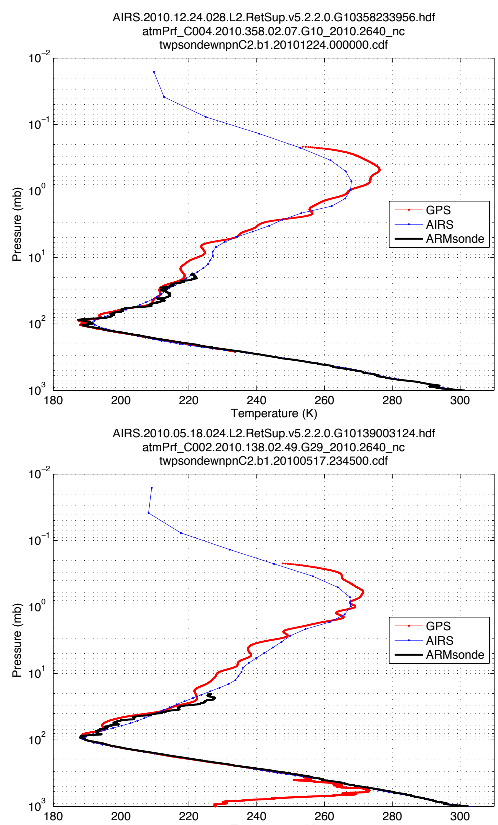
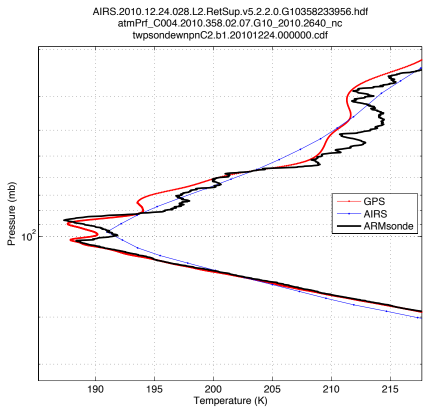


Figure 10. Overlaid COSMIC RO, AIRS, and radiosonde temperature profiles for 24 December 2010 at about 00 UTC (upper) and 17 May 2010 at about 23:45 UTC (lower).



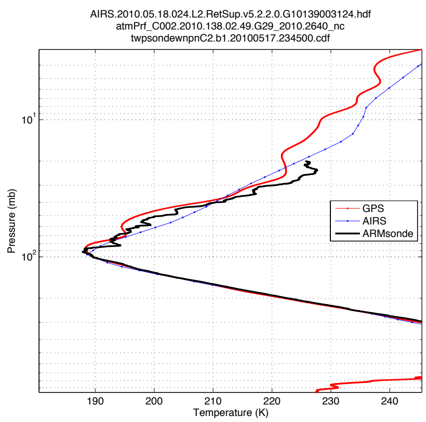


Figure 11. Close up of COSMIC RO, AIRS, and radiosonde temperature profiles near the tropopause for 24 December 2010 at about 00 UTC (upper) and 17 May 2010 at about 23:45 UTC (lower).

5. CONCLUSIONS

We developed the matchup tools for the comparison of COSMIC RO and AIRS IR temperature profiles. We found that a one hour time difference between GPS RO and the IR profile measurement provides adequate yield with sufficient accuracy to characterize bias and RMS errors for 20 degree latitude zones. When GPS RO horizontal averaging was applied to the AIRS Level 2 granule matchups, improved agreement was obtained compared to using the closest AIRS IR profile. Daily zonal statistics were found to provide a useful measure of AIRS retrieval performance. We anticipate that monthly time series for latitude zones can be used to monitor CrIMSS retrieval performance.

This study shows RMS error is between 1.5 K and about 2 K for the 300 mb to 30 mb altitude range for all latitude zones. Above this range, the COSMIC RO profiles appear to have higher vertical resolution than the AIRS IR profiles. Below this range, the COSMIC RO profiles become strongly contaminated by water vapor in the occultation ray path. The height of this effect is latitude dependent. These results are in qualitative agreement with results of Yunck et al. 2009. Comparison to ARM radiosondes from the Tropical Western Pacific generally confirm these conclusions.

Future work includes the application of the AIRS temperature averaging kernel to the COSMIC minus AIRS profile differences to remove vertical structure higher than the theoretical AIRS resolution. Application of this method to CrIMSS EDR products is in progress and will be reported in a future paper.

Acknowledgment

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