Optimizing the Source Surface Height of an Empirical Coronal Model During Solar Cycle 23 Minimum Using Remote and In Situ Measurements

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Optimizing the Source Surface Height of an Empirical Coronal Model During Solar Cycle 23 Minimum Using Remote and In Situ Measurements

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Introduction

- The Potential Field Source Surface (PFSS) model is a simple method for approximating the coronal magnetic field. The model assumes a spherical source surface exists around the sun (see **Figure 1**) where all the solar magnetic field lines are completely radial (Shatten et al. 1969)
- Several studies argue that during periods of solar minimum, the traditional source surface height (radius) of 2.5 solar radii may need to be lowered significantly to produce PFSS results that better match measured data at 1 AU (Lee et al. 2011; Nikolic 2019)
- We further investigate these claims by computing PFSS solutions for the solar cycle 23 minimum period using a high-performance finite difference solver called POT3D (Caplan et al. 2021) with magnetograph data from the Global Oscillation Network Group (GONG) and comparing these results to Synoptic maps from the McIntosh Archive, EUV images, and OMNI data
- We do this with the hopes of improving the modeling of space weather which is essential for the health of much of our technology like satellites and power grids

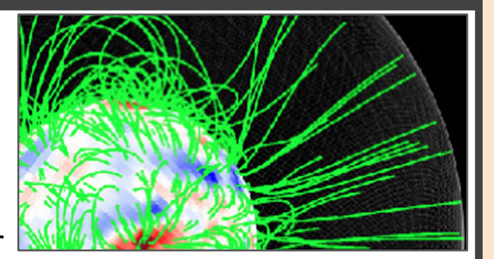
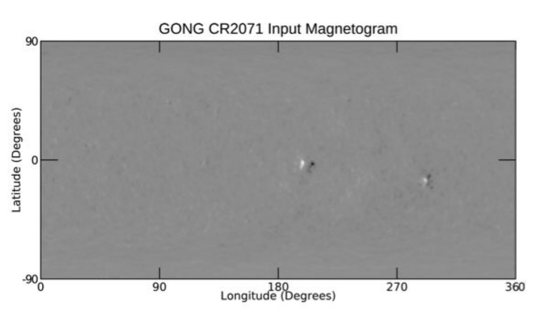
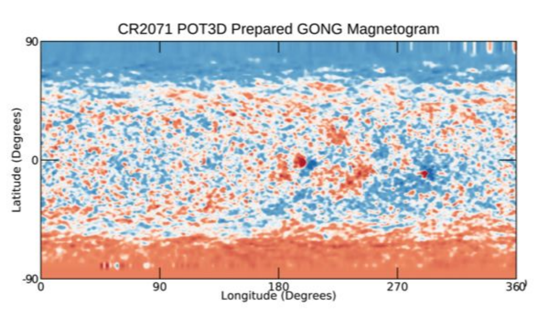
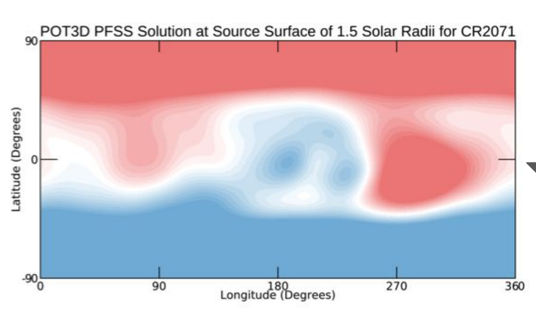


Figure 1. POT3D PFSS generated magnetic field lines from the photosphere to the source surface. Notice the lines are completely radial once they reach the source surface which is represented by the clear bubble feature. Image is originally from Caplan et al. 2021

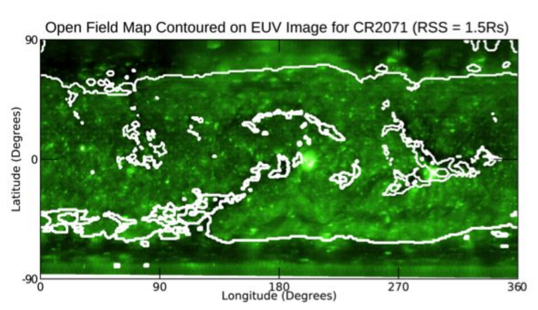
Methods

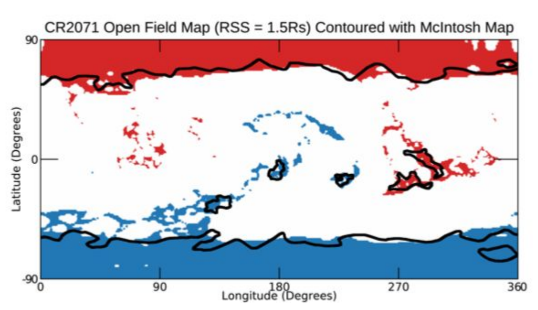


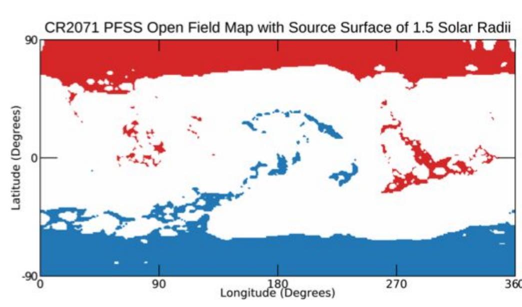




- (1) Our first step was to take GONG pole-filled synoptic magnetograms for each Carrington Rotation of interest (Carrington Rotations 2066-73). White/black represent positive/negative polarity
- (2) The Magnetograms were then interpolated onto the POT3D grid. In this step, the data was multiplied by 1/.7 to adjust for GONG's under measuring of magnetic field data by ~30% (Riley et al. 2014). Here White/black have been change to orange/blue for easier visualization.
- (3) Using the the GONG data, PFSS solutions at Carrington Rotations 2066-73 with Source Surface heights 1.5-2.5 Solar Radii were calculated with POT3D (see Caplan et al. 2021). This data was then used to predict the average radial magnetic field strength at 1AU (more on this in **Results**)







- (4) The PFSS solutions from the previous step were traced back from the source surface to the photosphere, creating open field maps, which show coronal holes (blue/red for positive/negative polarity)
- (5) Every coronal hole map was then overlaid with the coronal hole contours from the McIntosh Synoptic maps from the same Carrington Rotation (see **Figure 2** for McIntosh map example)
- (6) The open field maps from step (4) were then contoured onto EUV images (see **Figure 3.1**) as an additional check for coronal hole matching

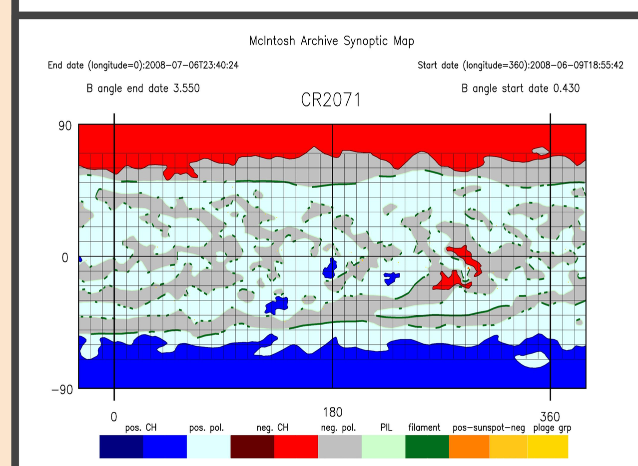


Figure 2 Sample McIntosh Synoptic map from Carrington Rotation 2071. These hand-drawn maps are derived from the He 10830A data from NSO observatories (Hewins et al. 2020).

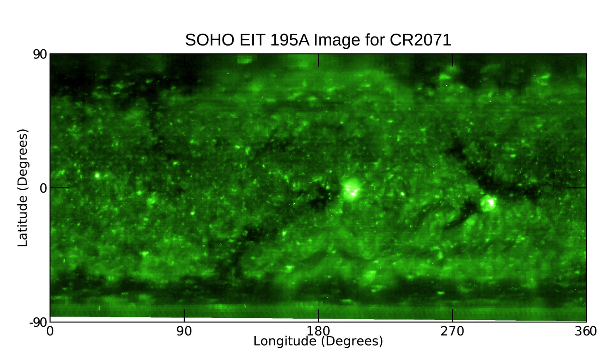


Figure 3.1 All EUV images used are from the SOHO EIT 195A band. The large dark features indicate coronal holes.

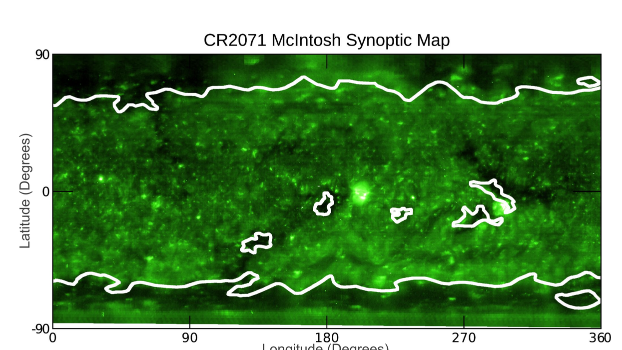


Figure 3.2 We also overlaid the McIntosh maps contours onto their corresponding Carrington Rotation EUV images to better see some of the differences between the two.

Results & Analysis

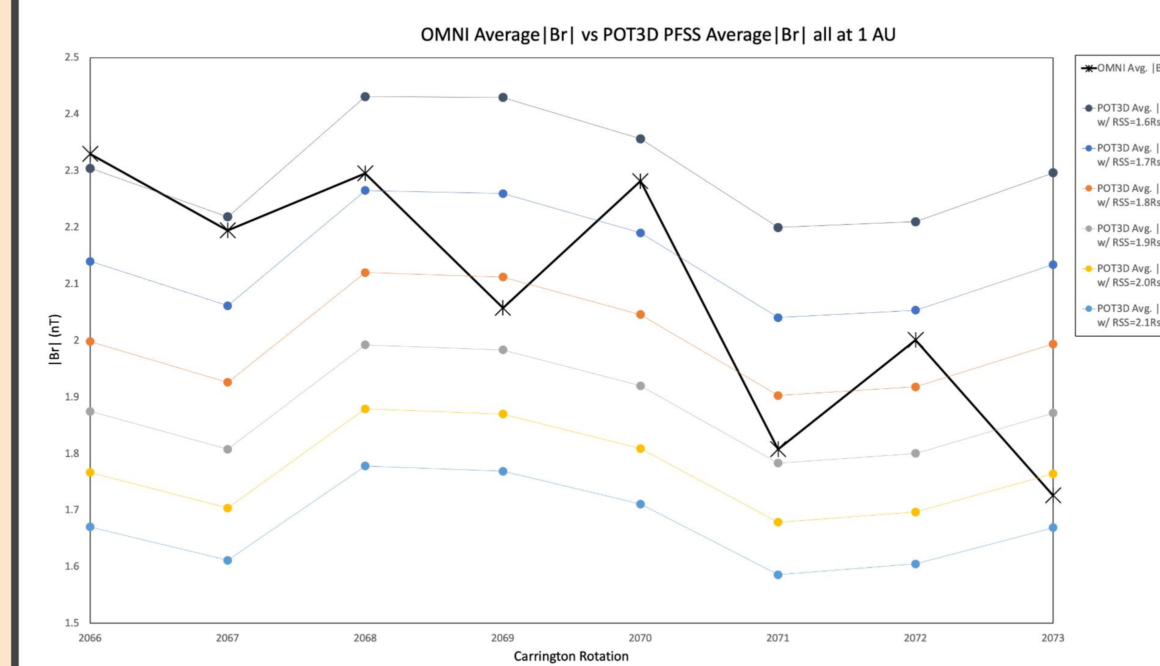


Figure 4. PFSS average magnetic field values at 1 AU compared to remote observations from OMNI. Data from source surface heights 1.5, 2.2, 2.3, 2.4 and 2.5 solar radii have been omitted.

Approximate Best Fit Source Surface Heights According to Values from **Figure 4**								
Date (CR)	2066	2067	2068	2069	2070	2071	2072	2073
SS Height (Rs)	1.6	1.6	1.7	1.8	1.6	1.9	1.7	2.1

Table 1. Roughly which source surface height from each Carrington Rotation matches the OMNI remotely measured data from **Figure 4**. Notice that, while there isn't a constant source surface height that matches the measured field strength, the maximum source surface height suggested by **FIgure 4** is 2.1 solar radii, which is significantly less than the traditional value of 2.5 solar radii.

- **Figure 4** and **Table 1** show the PFSS predicted magnetic field values at 1AU. These values were calculated by averaging the magnitude of the PFSS radial magnetic field at the source surface. This data was then multiplied by the quotient of the source surface height and the distance from the sun to the earth in solar radii squared to extrapolate the data out to 1 AU (Smith et al. 2008)
- The results in **Table 1** results indicate that the optimal source surface height varies depending on time
- For Carrington Rotations 2066-73 an average source surface height of ~1.75 solar radii is best when compared to OMNI's remotely measured magnetic field data at 1 AU
- To qualitatively compare the results in the figures above to another source of magnetic field measurements, **Figure 5** shows PFSS open field maps with the optimal source surface heights suggested by **Table 1** and the traditional height of 2.5 solar radii contoured with McIntosh synoptic maps from the same Carrington Rotation
- For most of the chosen dates, it appears that the **Table 1** source surface height in **Figure 5** matches more features, but in some cases overestimates the area of the coronal holes

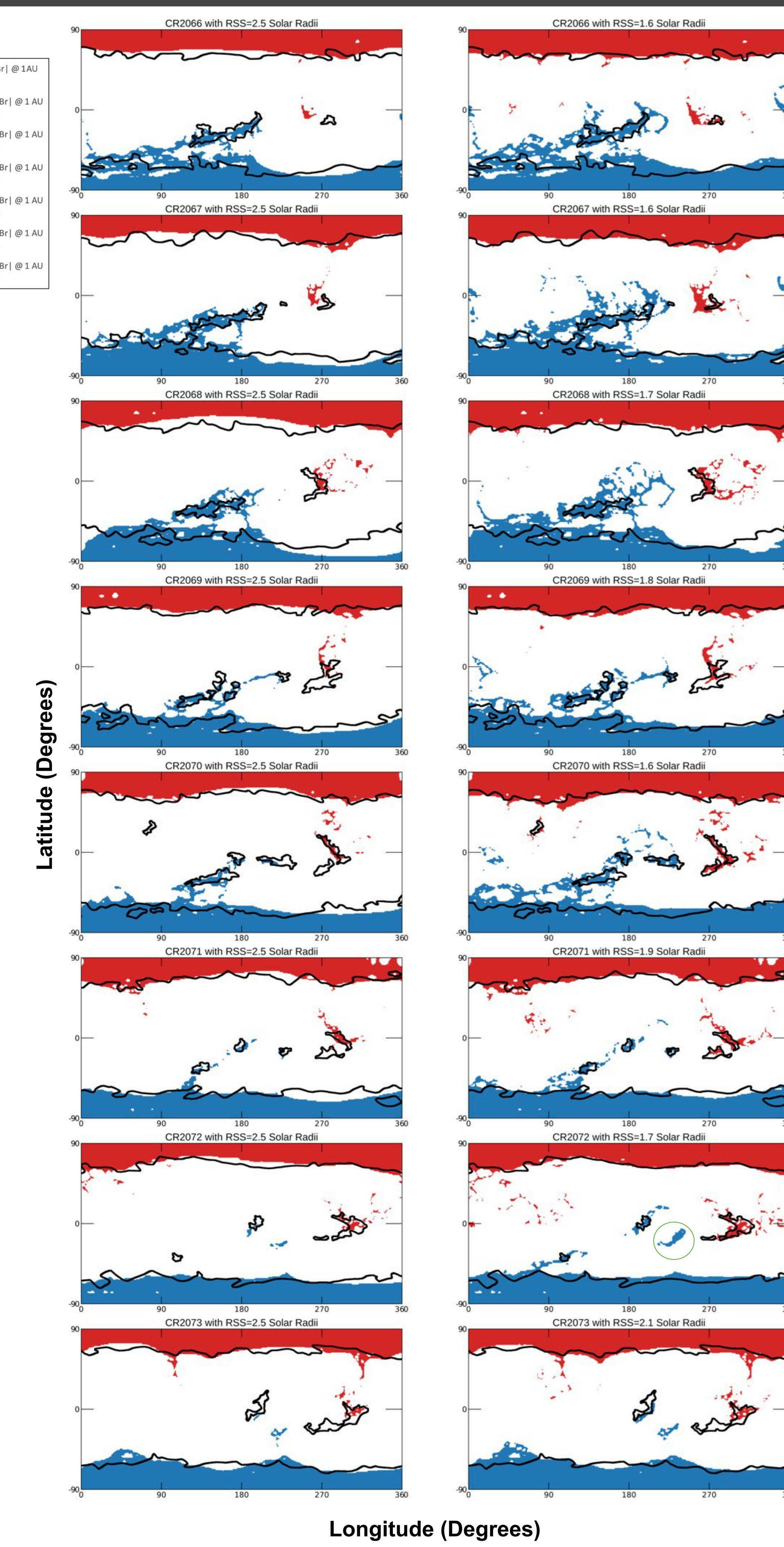


Figure 5. PFSS generated open field maps contoured with McIntosh synoptic maps from the same date. The green circle in CR2072 RSS=1.7 solar radii map indicates a large low-latitude coronal hole that is missing from the McIntosh contour.

- Many of the open field maps in the right column of **Figure 5** also contain regions where there appear to be 'specs' and tiny scattered areas of open fields. These regions are difficult to identify on both the McIntosh maps and EUV images, which mostly show large-scale coronal hole features. Because of this, our study mostly focused on matching easily identifiable large features.
- There are some closed field regions in the polar coronal holes appearing as white holes in **Figure 5** that do not change with varying source surface heights. These structures may be related to the high uncertainties around the poles in the GONG magnetograms. We disregard these structures in our visual comparisons.
- The McIntosh Synoptic maps provide a good baseline for identifying the major coronal holes in the PFSS open field maps but not necessarily all coronal holes since they are hand-drawn interpretations of measurements of the photosphere
- For example, the circled feature in **Figure 5** for Carrington Rotation 2072, the PFSS solution with a source surface of 1.7 solar radii agrees mostly with the McIntosh synoptic map contour. However, the green circle indicates a coronal hole that was predicted by the PFSS model, but that was not drawn on the McIntosh map.
- This circled feature is present on the EUV image in **Figure 6**. The EUV image overlays also shows that the McIntosh map contours seem to under represent coronal hole area. This indicates that there is some room for variation when qualitatively comparing these maps and with PFSS open field solutions. Combined with the sources of error listed above for the open field maps, we did not consider slight PFSS overestimates in **Figure 5** as an indication of a bad match. Therefore, the best source surface heights generally come from the data in the right column of **Figure 5**. Better fits also come from the bottom row of **Figure 6**, indicating that the lower source surface heights yield more accurate data

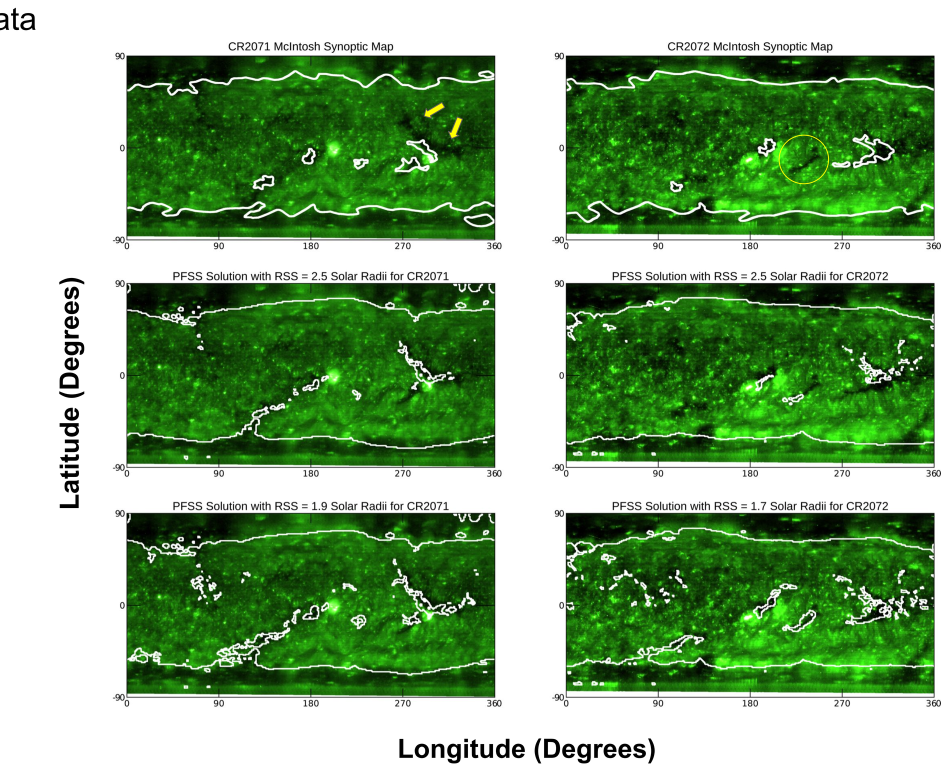


Figure 6. The title of each plot contoured on top of the SOHO EIT 195A image from the same date. Note that the top row is McIntosh map contours, while the bottom two rows are PFSS open field map contours. The yellow circle shows the PFSS predicted coronal not present on the McIntosh map contour for CR2072. The arrows point to a large coronal hole size underestimate by the McIntosh map contour.

Conclusions & Next Steps

- Our data suggests that, on average, the optimal source surface height for Carrington Rotations 2066-73 when using GONG pole corrected input magnetograms is ~1.75 solar radii. The various contour maps show this by revealing better matches, especially of low latitude coronal holes, with source surface heights closer ~1.75 solar radii. This result is consistent with finds of Lee et al. 2011 and Arden et al. 2014, which furthers the conclusion that the source surface should be lowered substantially to produce more accurate PFSS results for solar cycle 23 minimum.
- The next steps for this project are to expand the period of time we are looking at to cover the complete availability of GONG data (2006-present). From here, we will use coronal hole detection tools (Linker et al. 2021) to more accurately identify these features in EUV images. This coronal hole tracing will give us another tool to quantitatively compare our PFSS open field maps with. The traced EUV images will also allow us the use of numerical methods to compare coronal hole area from several different sources along with other numerical quantities in addition to the visual comparison .

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- GONG: https://gong.nso.edu
- SOHO EIT 195A Images: http://spaceweather.gmu.edu/projects/synop/EITSM.html

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