Two old studies that are *somewhat* interesting and *probably* worth sharing.

September 3, 2018

Part One:

A model of manual control for a single shade in a single context.

Preface

- Predicting manual shade operation presents a persistent challenge to energy modelers and daylight simulators.
- There is some understanding of what event types trigger manual shade operation (direct sunshine, sky glare, reflected glare, etc.), though observed trigger thresholds vary.
- We have little understanding of how long a shade remains lowered after a triggering event ends. This manual shade delay likely depends on both type of event and attentiveness of the user.

Manual Shade Position Measurements

- In Arup's SF office, we monitored manual shade movements for two shades over a five month period.
- We measured the height of the shade above the floor by placing a drawstring potentiometer placed on the floor and attaching the string to the bottom of the shade.

- Also measured environmental conditions
  - Transmitted facade irradiance
  - Workplace illuminance
  - Temperature
  - Humidity
  - Mean radiant temperature

Exterior Conditions

- Over the course of our study we have observed regular shade deployment on sunny mornings when the sun appears from behind an neighboring building. Roughly 90 minutes later the sun disappears behind another building (see photo of view from the desk).
- From the monitored data we can determine the time the sun disappears and the time the shade is raised. The difference between these times is a delay in occupant response. We have observed 37 instances of the event and subsequent shade operation over the duration of our monitoring.

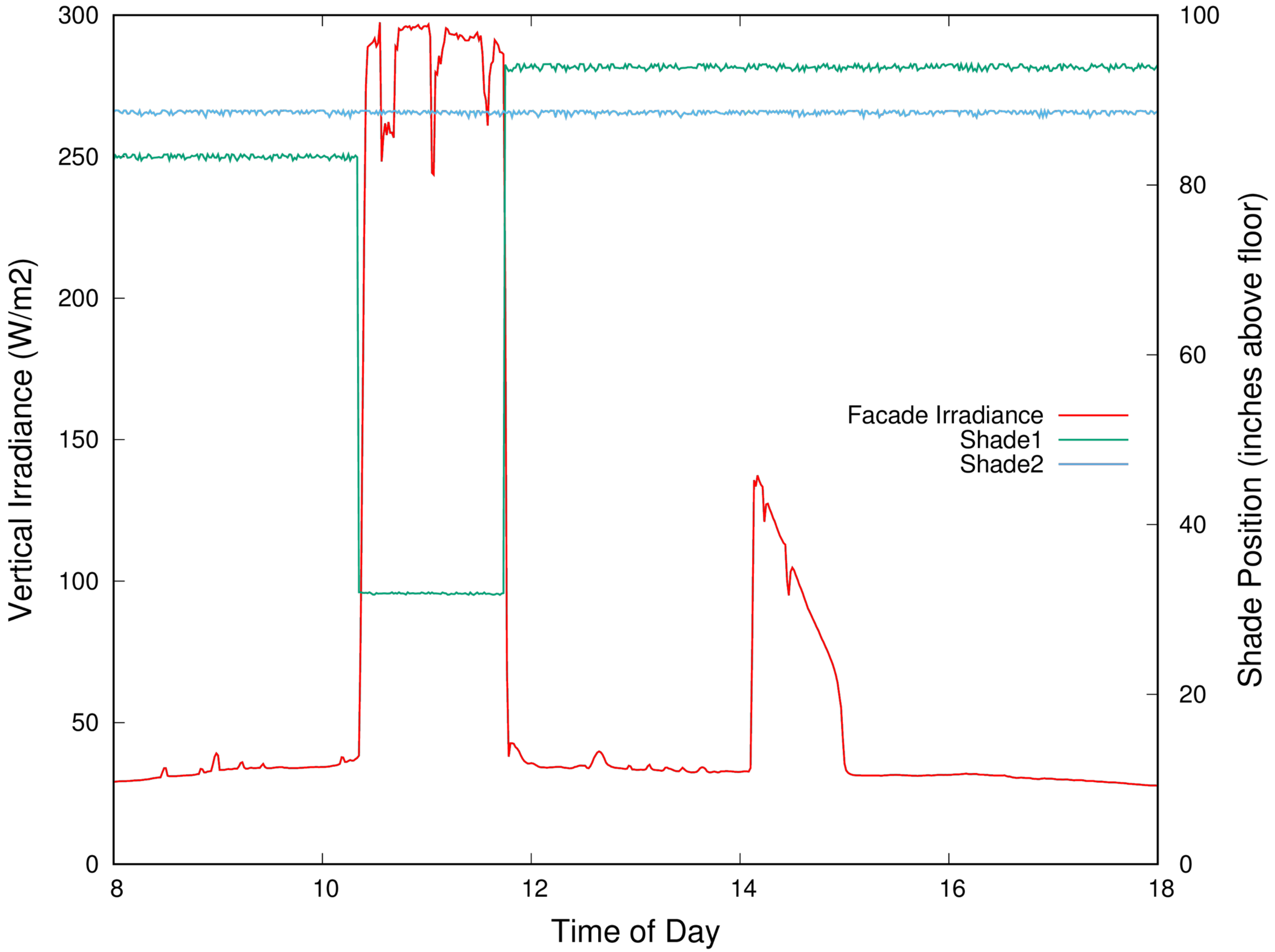
View out the window from the desk studied.

Occupants

- The shade was shared by two Arup employees:
  - Both Lighting Designers.
  - Keenly aware of benefits of daylight.
  - Socially conscious, and felt a sense of duty to provide daylight to other employees in the office.
  - Both aware that we were measuring their blind use.

  - Possibly the most active blind users in the world.

Attentive Shade Control - November 3



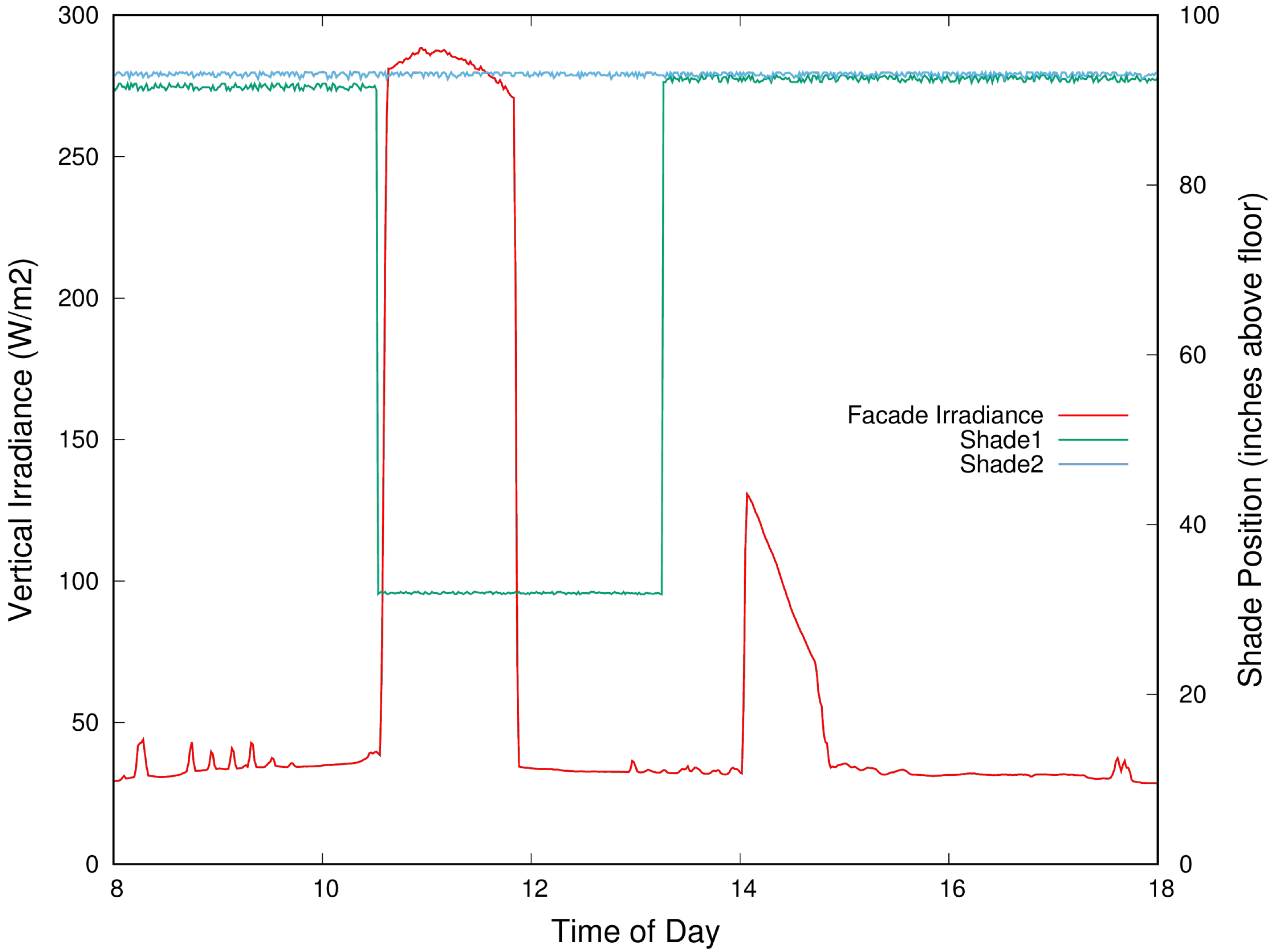
10:15

- Sun shines on facade (red line)
- Shade lowered (green line)

11:45

- Sun stops shining on facade (red line)
- Shade raised (green line)

Less Attentive Shade Control - October 21



10:25

- Sun shines on facade (red line)
- Shade lowered (green line)

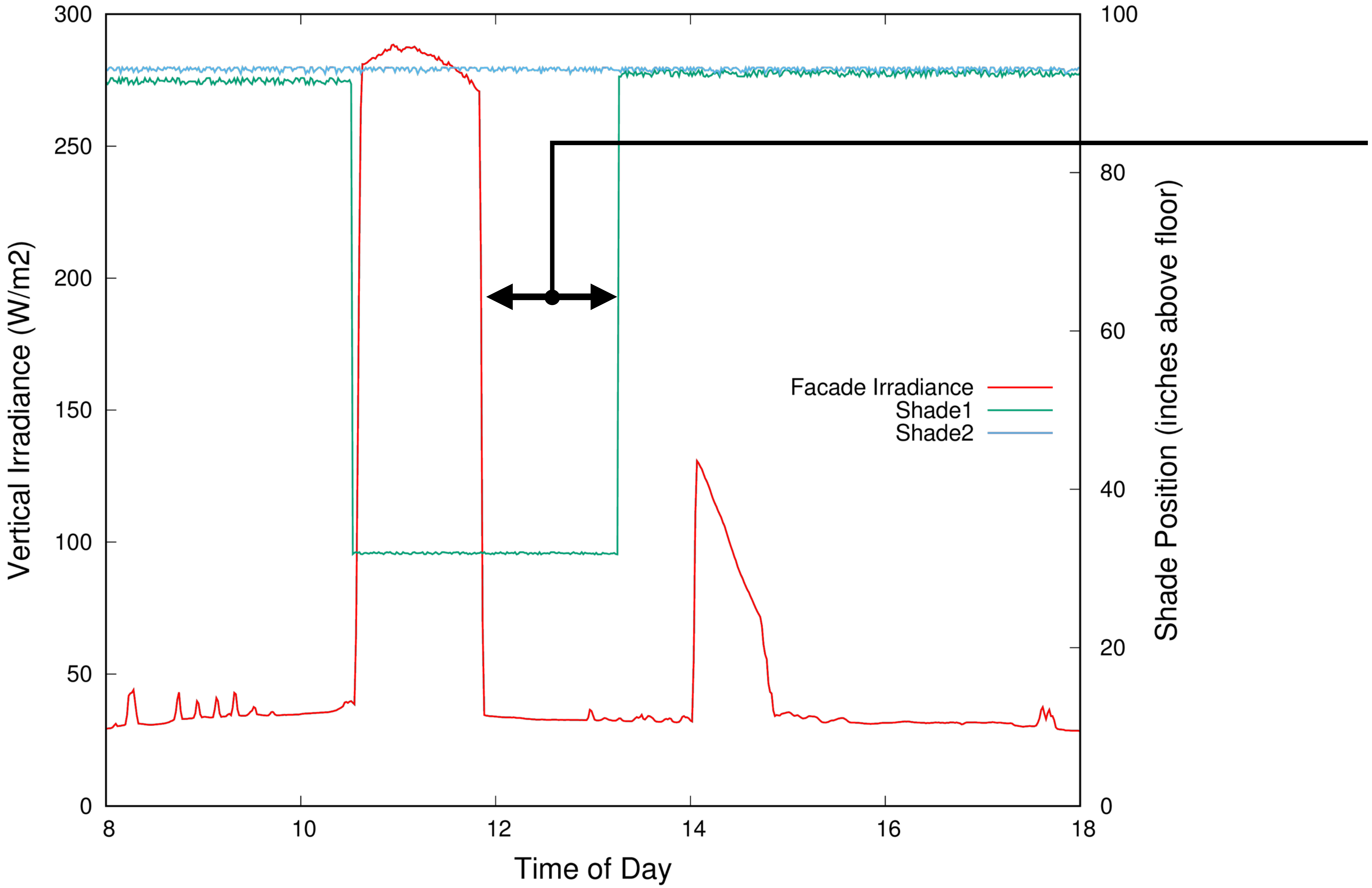
11:53

- Sun stops shining on facade (red line)

13:16

- Shade raised (green line)

Determining response time for manual shade adjustment



83 Minutes between the end of sun shining on the facade and the shade movement.

All 37 occurrences observed

Month	Day	Sun Time	Shade Time	Delta
9	2	13:17	13:59	42
9	7	13:04	13:15	11
9	9	12:58	13:54	56
9	13	12:50	13:04	14
9	14	12:47	12:50	3
9	15	12:46	13:29	43
9	16	12:42	13:41	59
9	19	12:36	13:05	29
9	20	12:34	13:10	36
9	21	12:32	12:38	6
9	22	12:30	12:39	9
9	23	12:29	15:01	152
9	26	12:22	19:00	398
9	27	12:20	12:35	15

Month	Day	Sun Time	Shade Time	Delta
9	28	12:19	12:52	33
9	30	12:15	12:30	15
10	4	12:08	13:10	62
10	5	12:07	12:11	4
10	6	12:05	13:04	59
10	7	12:04	12:58	54
10	10	12:00	13:09	69
10	11	12:02	13:08	66
10	13	12:00	12:16	16
10	17	11:54	12:03	9
10	18	11:54	12:03	9
10	19	11:54	12:05	11
10	20	11:53	12:08	15
10	21	11:53	13:16	83

Month	Day	Sun Time	Shade Time	Delta
10	26	11:50	13:04	74
11	1	11:38	12:09	31
11	2	11:47	12:05	18
11	3	11:45	11:45	0
11	4	11:46	11:47	1
11	7	11:30	13:55	145
11	8	10:45	11:30	45
11	9	10:45	10:52	7
11	10	10:46	10:57	11

Fitting observed response times to a log-normal distribution

Log normal probability distribution function:

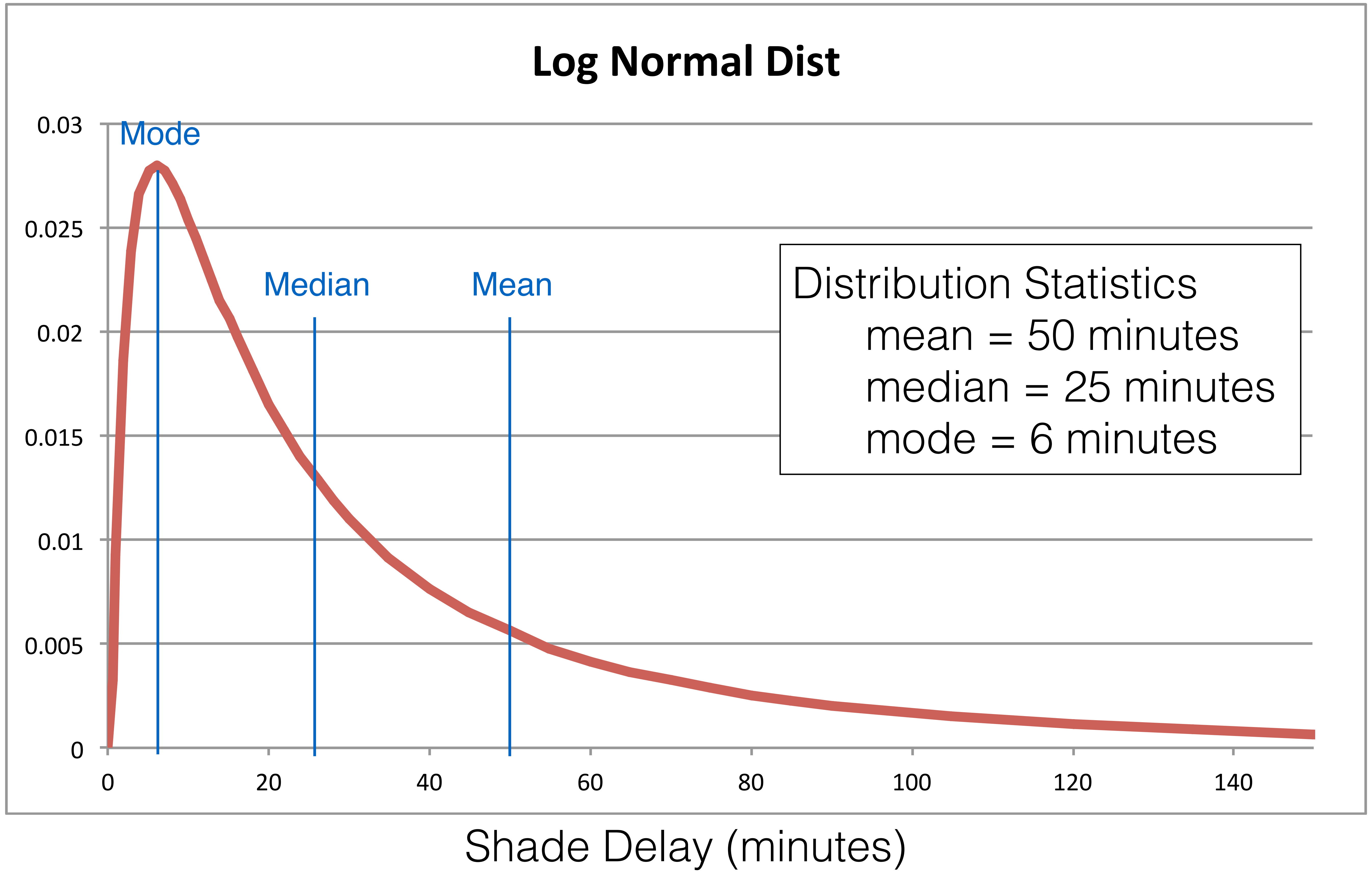
$$\mathcal{N}(\ln x; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right]$$

Fitting observed data to a log-normal distribution using results in the following values for μ & σ

μ = 3.1959

σ = 1.1991

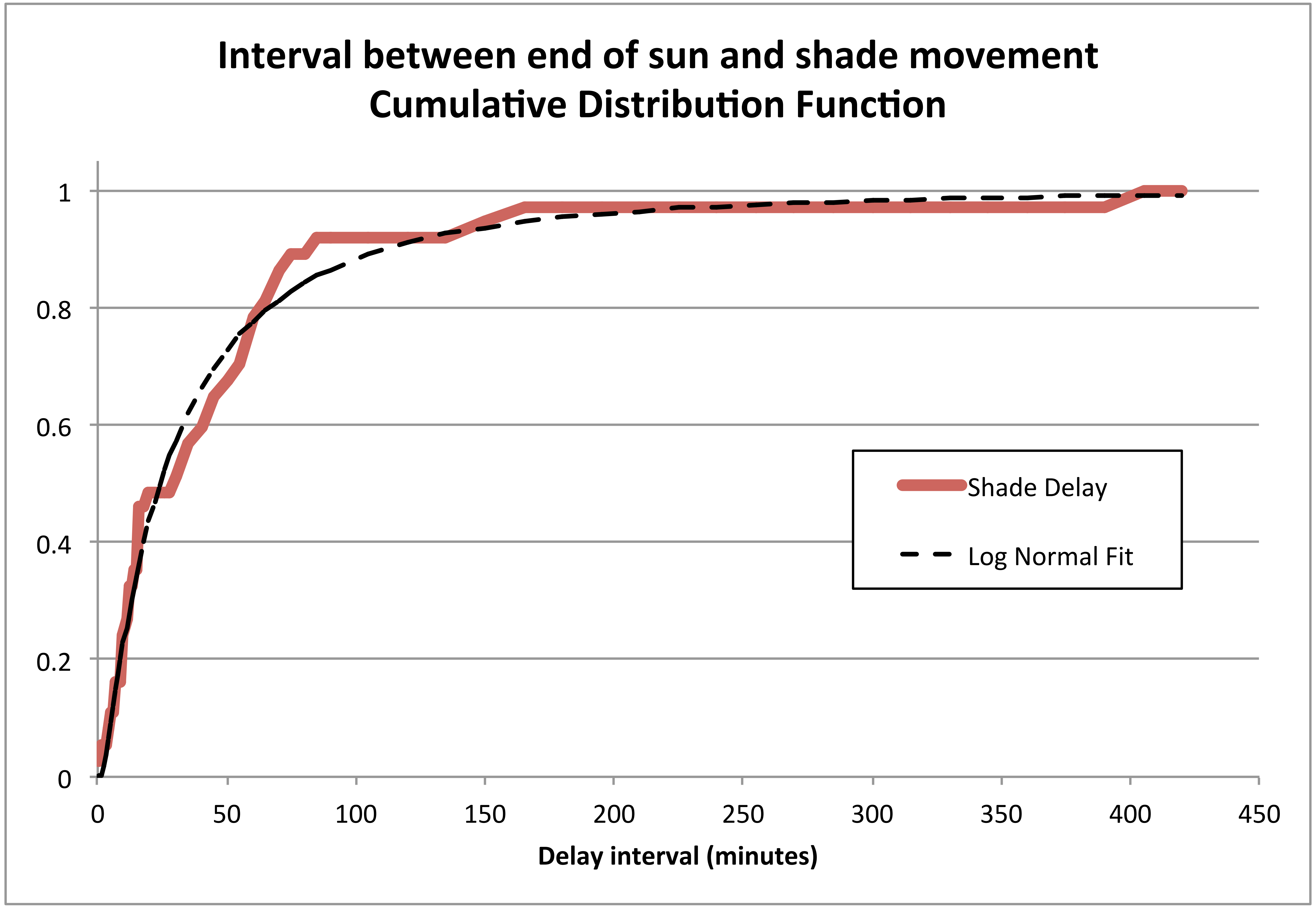
fit performed using:
http://www.wessa.net/rwasp_fitdistrlnorm.wasp



Comparing observed and fit cumulative distribution function

A good way to visually compare the observed data and the log-normal probability distribution fit to the data is with the cumulative distribution functions (CDF).

The chart to the right shows the observed CDF in red and the fit CDF in black.

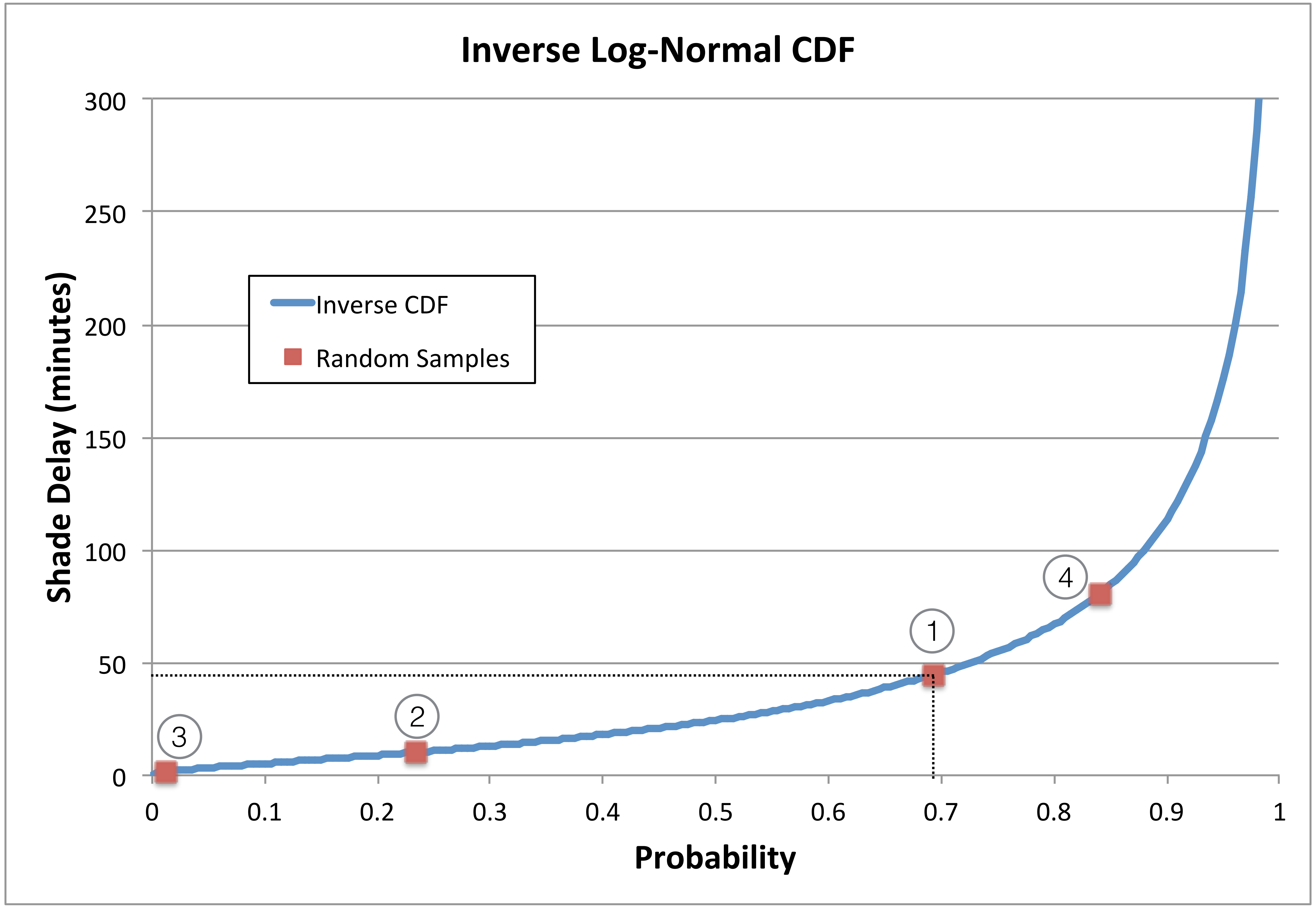


Simulating manual shade operation using inverse CDF

We can use the observed data to model the delay manual shade operating response in building simulations. We would begin by inverting the CDF. Then, for each event, we generate a random number from a uniform distribution in the range [0,1). The random number is fed to the inverted CDF to determine the shade delay for an event.

The table below shows random numbers generated for four events. The numbers are plotted on the inverted CDF, and the resulting delay is also shown in the table.

Event	Random Number	Shade Delay
1	0.6924	44.64
2	0.2344	10.25
3	0.0120	1.63
4	0.8408	80.81



Conclusion and Discussion

- Characterized delay response for operation of a manual shade for **One** type of shade deployment event by **Two** (attentive) users.
- What’s missing (a lot, quite frankly):
  - More occupant profiles
  - Understanding of thresholds and other trigger events

Part Two:

Optimizing the grouping of PV panels for a large and unusual rooftop PV installation.

Challenges:

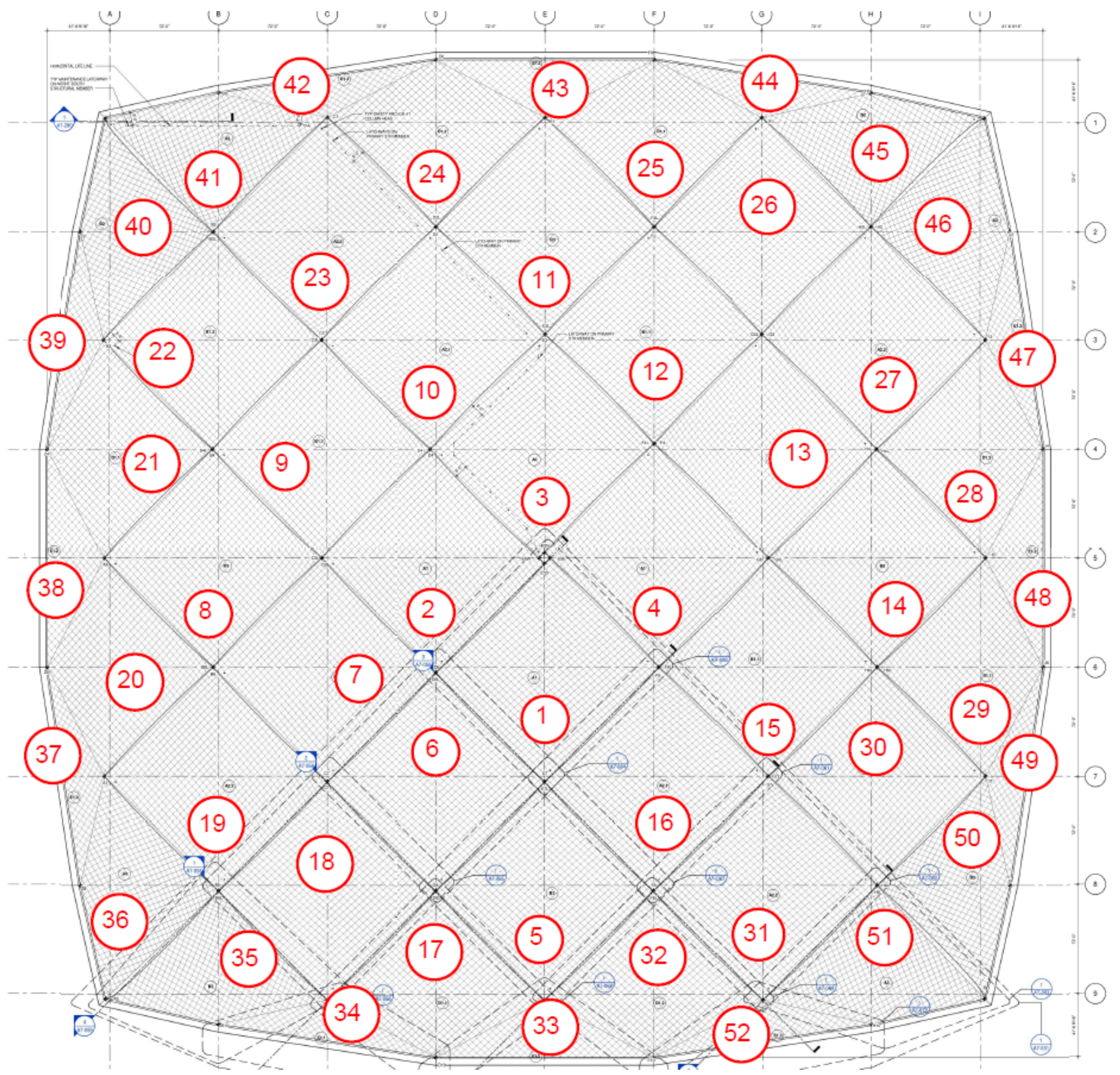
- Each PV is aimed at a slightly different angle.
- Clerestories shade panels along some of the bay edges.

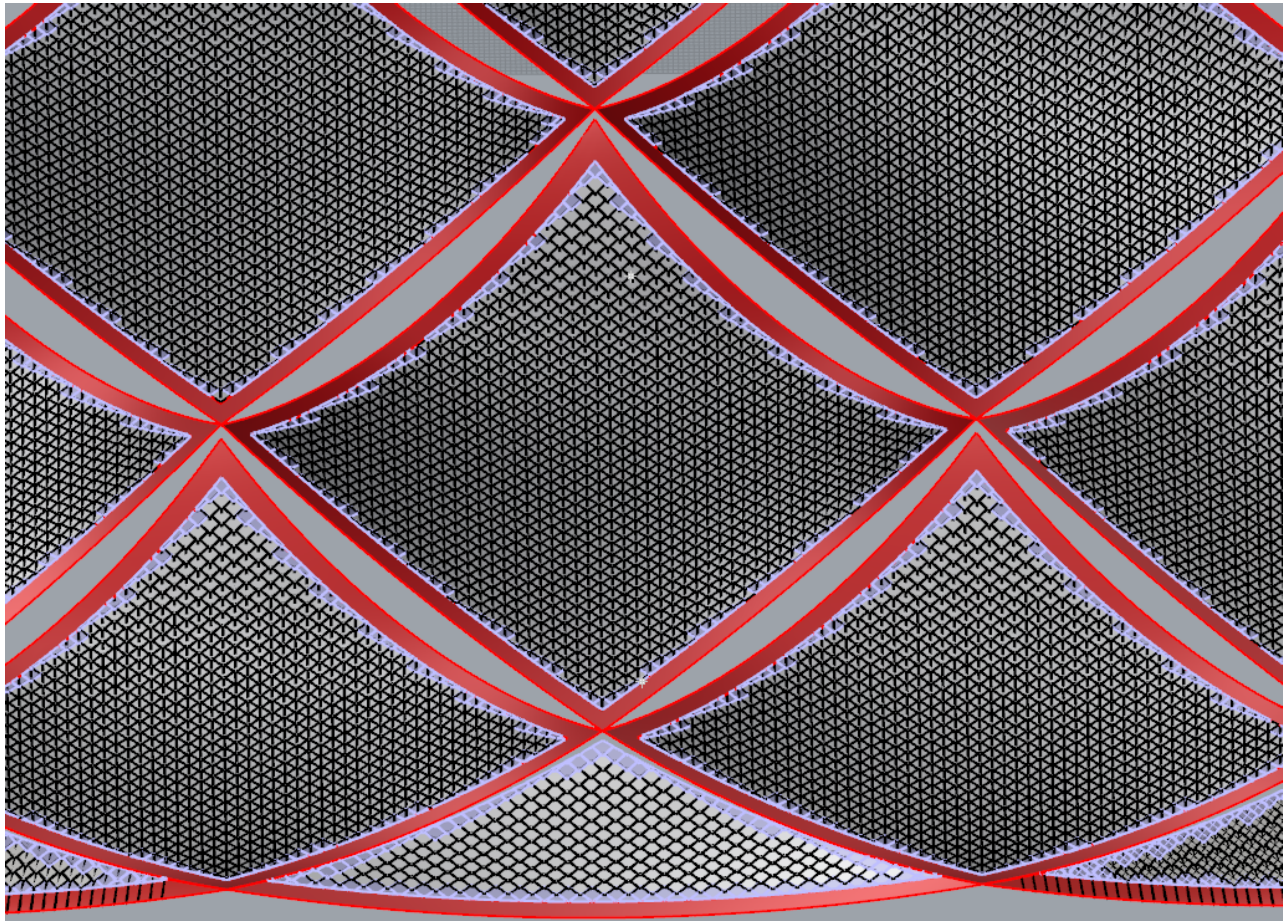
Estimating Output of Rooftop PV

Process:

Step 1 – Group panels based on irradiance profile

Step 2 – Estimate hourly energy production



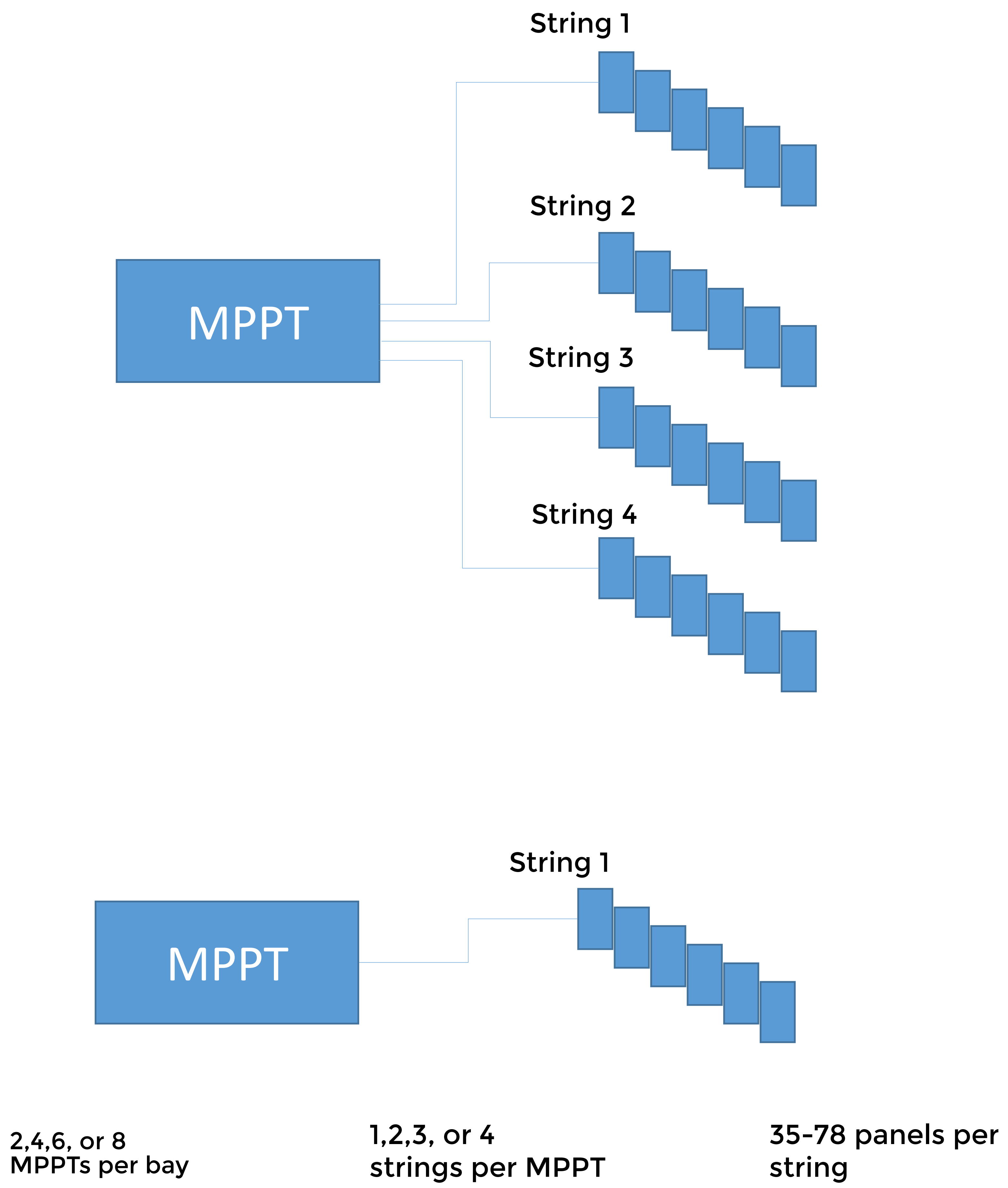


Step One

Grouping Panels

Zoning PV panels

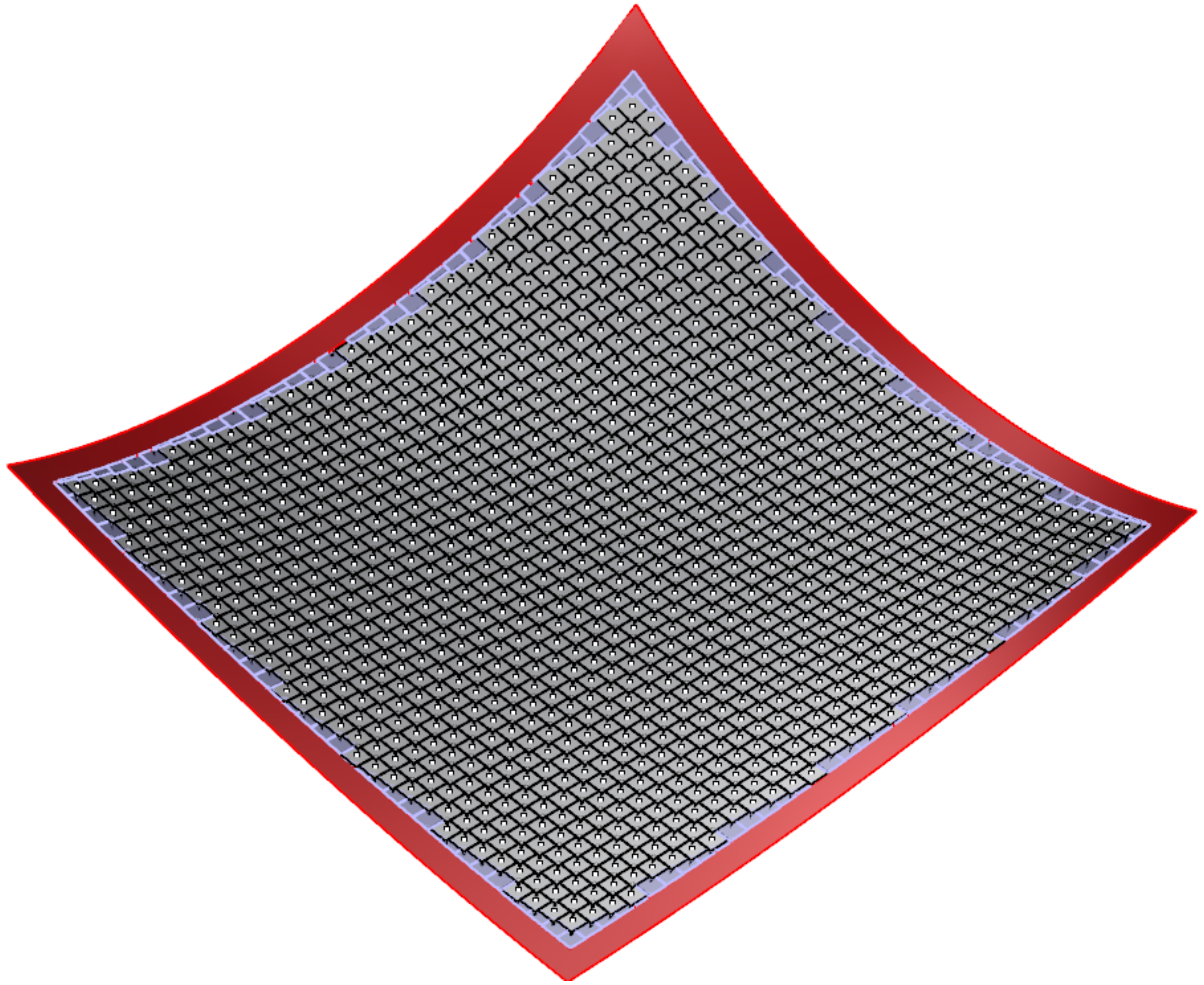
- **Each roof bay has 2-8 MPPTs**, depending on the size of the bay. Each panel on the roof is connected in a string to one of the MPPTs.
- The output of each MPPT is limited by the least producing panel on the string. The optimal zoning groups panels with similar production profiles.
- Each MPPT can serve 35 - 312 panels. However, each MPPT has a 15kW max output. When the power produced by panels exceeds the max output for the MPPT, the additional power is lost. To avoid exceeding 15kW the maximum number of panels is reduced to 220.
- The practical range is **35-220 panels per MPPT**, therefore groups are restricted to this range.



Hourly irradiance simulation details

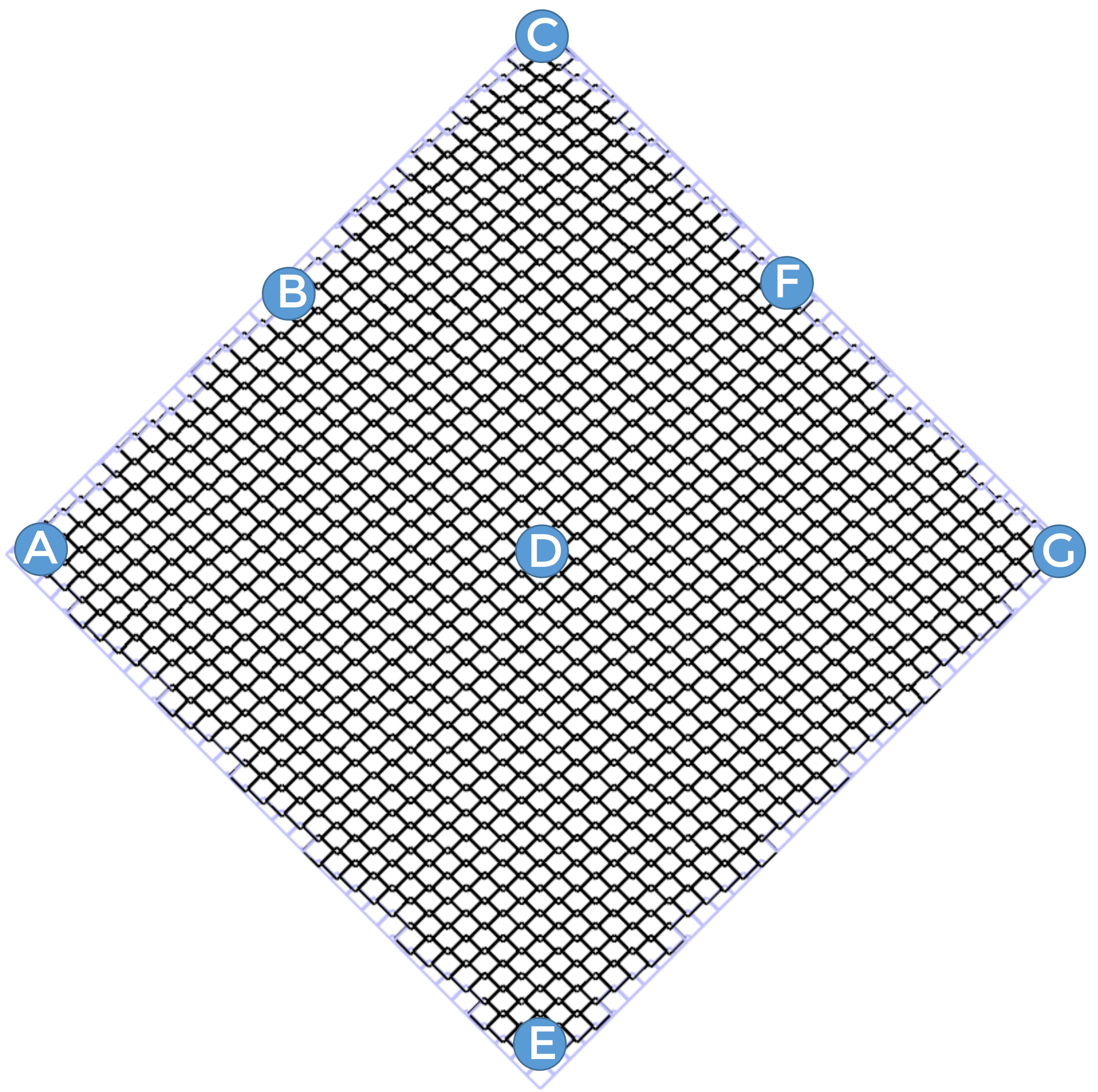
Simulation procedure for determining incident irradiance on panels:

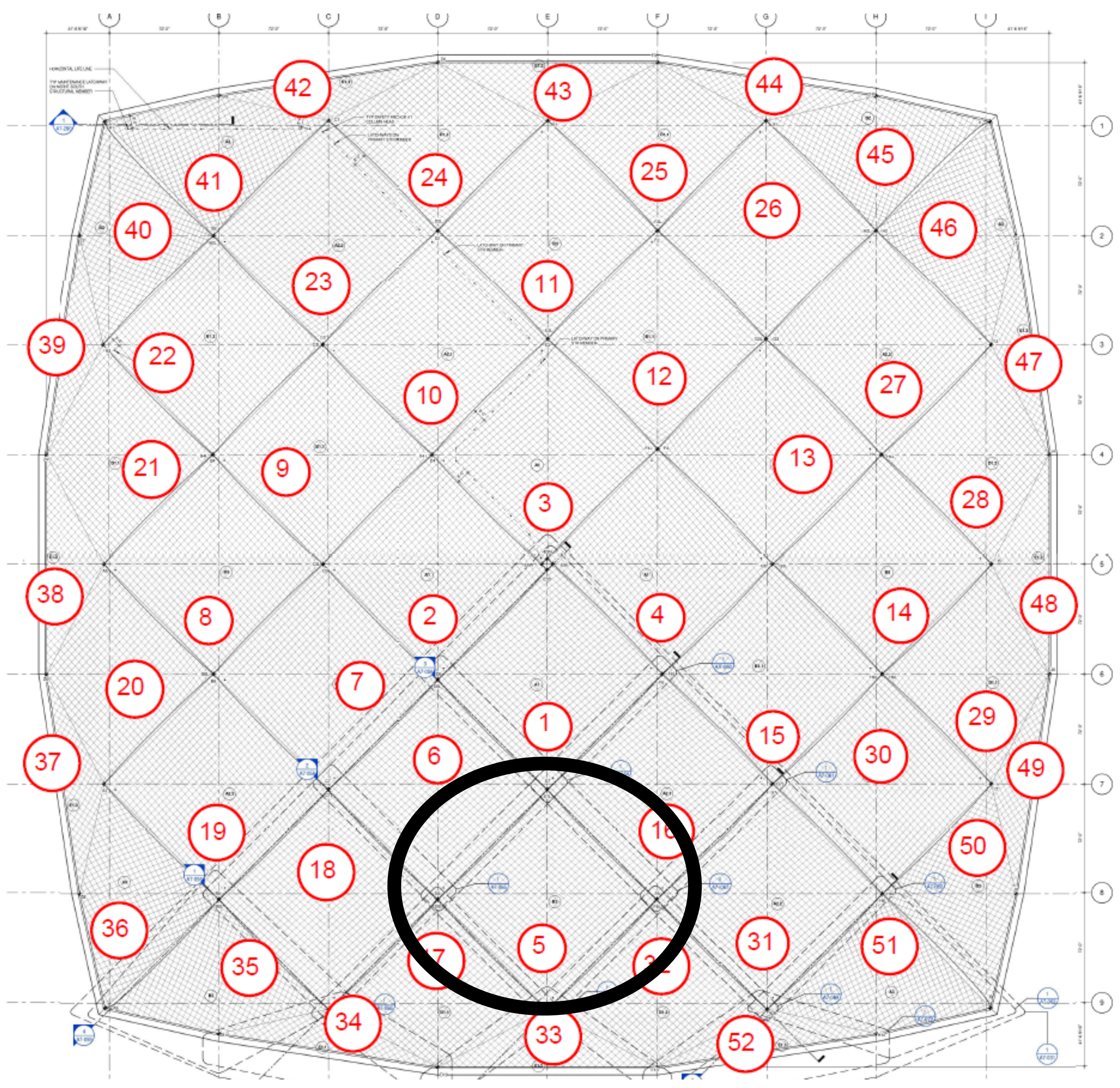
- An analysis point is positioned at the center of each panel in the Rhino model. Point coordinates are exported to a text file.
- The Radiance program ‘rtrace’ traces a ray originating 1cm above the analysis point in the –Z direction. Rtrace returns the normal direction of the intersected surface (the PV panel). The analysis point and surface normal are written to a separate text file for analysis.
- The Radiance program ‘rfluxmtx’ uses the analysis points and surface normal to create a daylight coefficient matrix. The daylight coefficient matrix uses the reinhart M4 sky subdivision, with 2305 sky patches.
- The Radiance program ‘gendaymtx’ creates a sky matrix based on the Moffett Field weather data file. The –O1 option is used with gendaymtx to generate a skymatrix of total solar radiance.
- The Radiance program ‘rmtxop’ multiplies the daylight coefficient matrix by the sky matrix, producing an irradiance matrix containing irradiance values for every panel and every hour of the year.



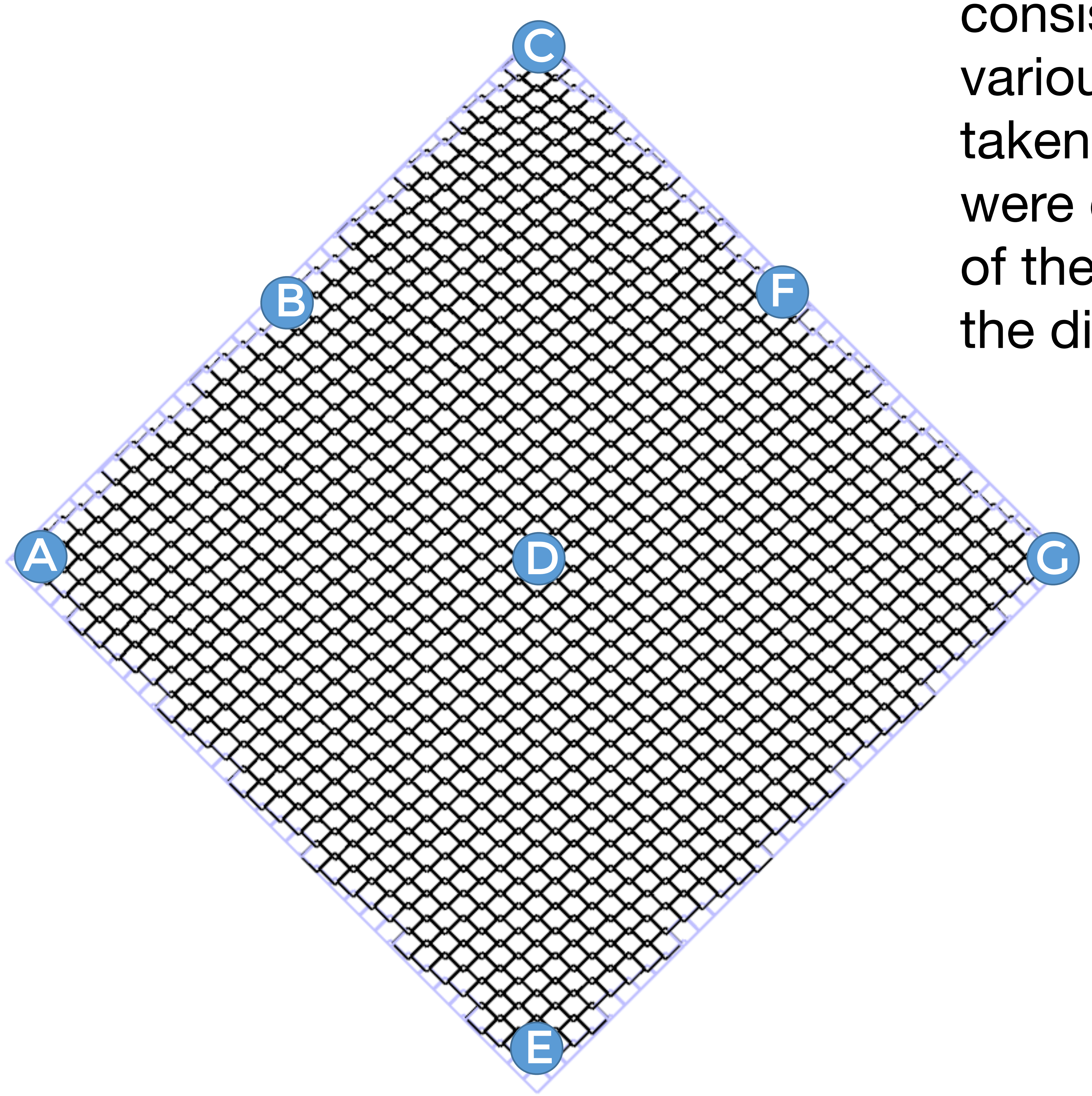
Determining PV groups – Bay05

- Panel layout for roof bay 05





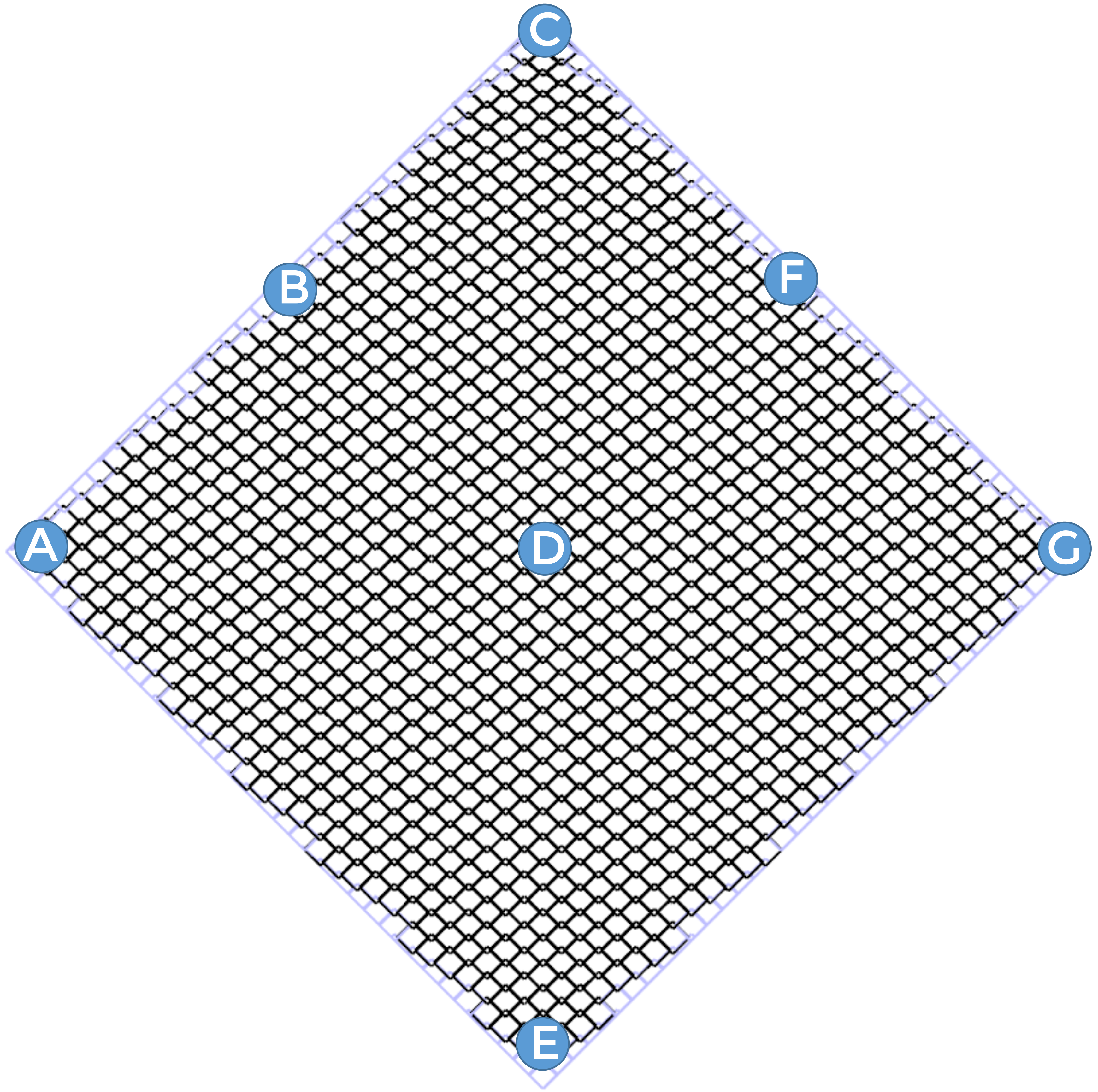
Determining PV zones – Bay05

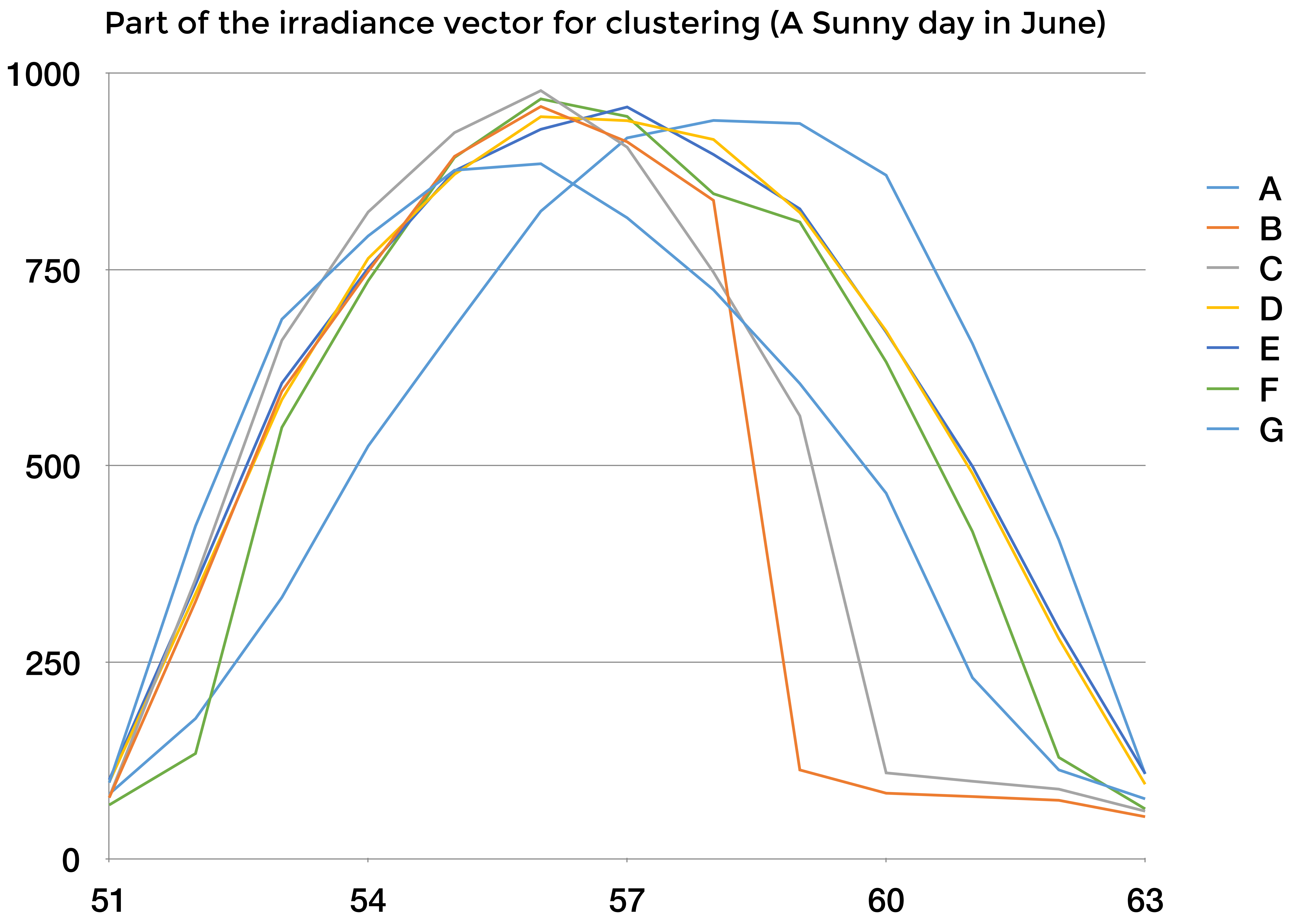


For this study, panel groups were determined using k-means clustering, using a vector of 73 dimensions. The vector consists of irradiance on the panel for various times of day and year. Times were taken from weather data. Only sunny days were chosen. The table below shows part of the vector for seven panels identified on the diagram to the left.

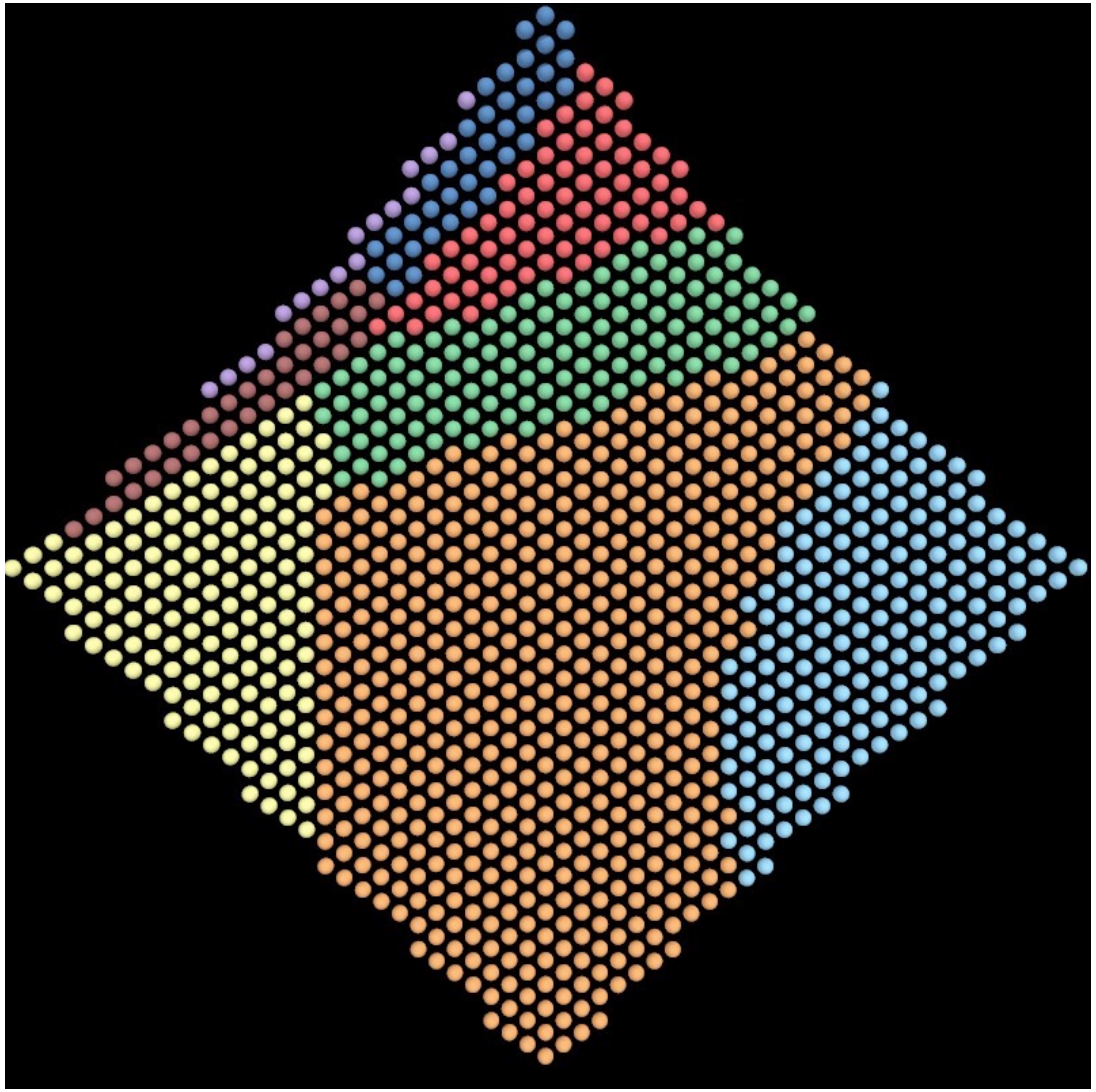
	A	B	C	D	E	F	G
I_1	240	346	626	281	314	337	147
I_2	297	476	791	399	460	481	307
I_3	317	519	810	495	504	538	457
I_4	275	529	794	523	552	576	524
I_5	192	500	697	475	513	543	614
I_6	111	65	489	368	417	396	546
…	…	…	…	…	…	…	…
I_{51}	97	78	78	97	100	68	82
I_{52}	423	327	356	337	349	134	178
I_{53}	686	595	660	584	605	549	332
I_{54}	792	747	823	764	751	735	525
I_{55}	876	894	924	871	875	892	676
I_{56}	884	957	977	944	928	967	824
I_{57}	815	912	905	939	956	944	917
I_{58}	724	838	746	915	896	846	939
I_{59}	605	113	564	822	827	810	935
I_{60}	465	83	109	672	670	632	870
I_{61}	230	79	99	490	499	416	655
I_{62}	113	74	89	280	293	129	406
I_{63}	76	53	61	95	108	63	108
…	…	…	…	…	…	…	…
I_{73}	8	6	8	10	32	8	105

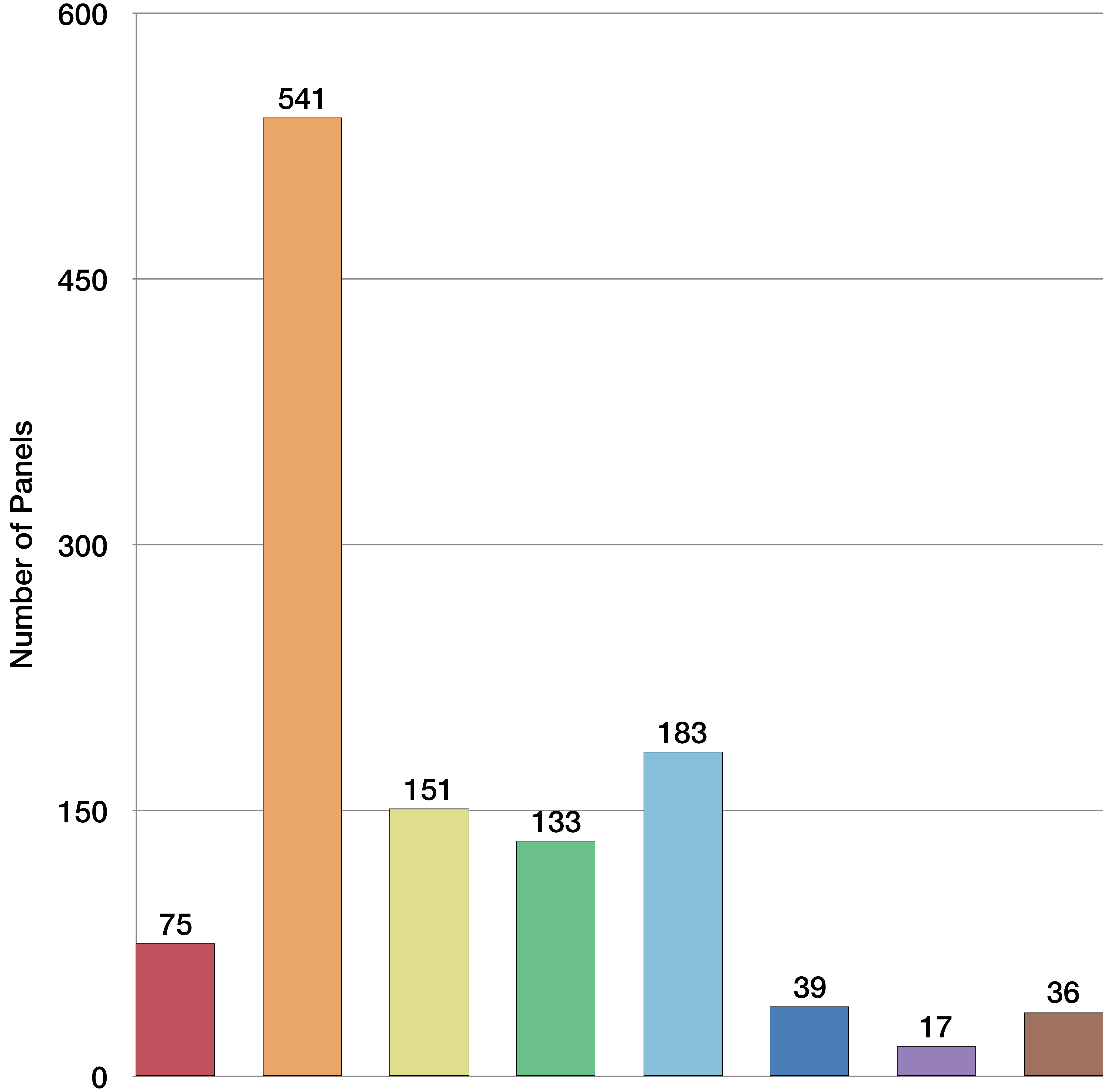
Determining PV zones – Bay05





Clustering Result - Bay 05





Constraining Number of Panels per Zone

- Of the clustering algorithms available, none have the ability to limit the size of clusters.
- The result of clustering for most bays includes zones with more than 220 panels.
- Generating PV zones that conform to limits of MPPTs requires reassigning panels to reduce the number of panels in zones exceeding the limit.

Constraining Number of Panels per Zone

Reassignment is performed based on Euclidean distance in 73 dimensional hyperspace.

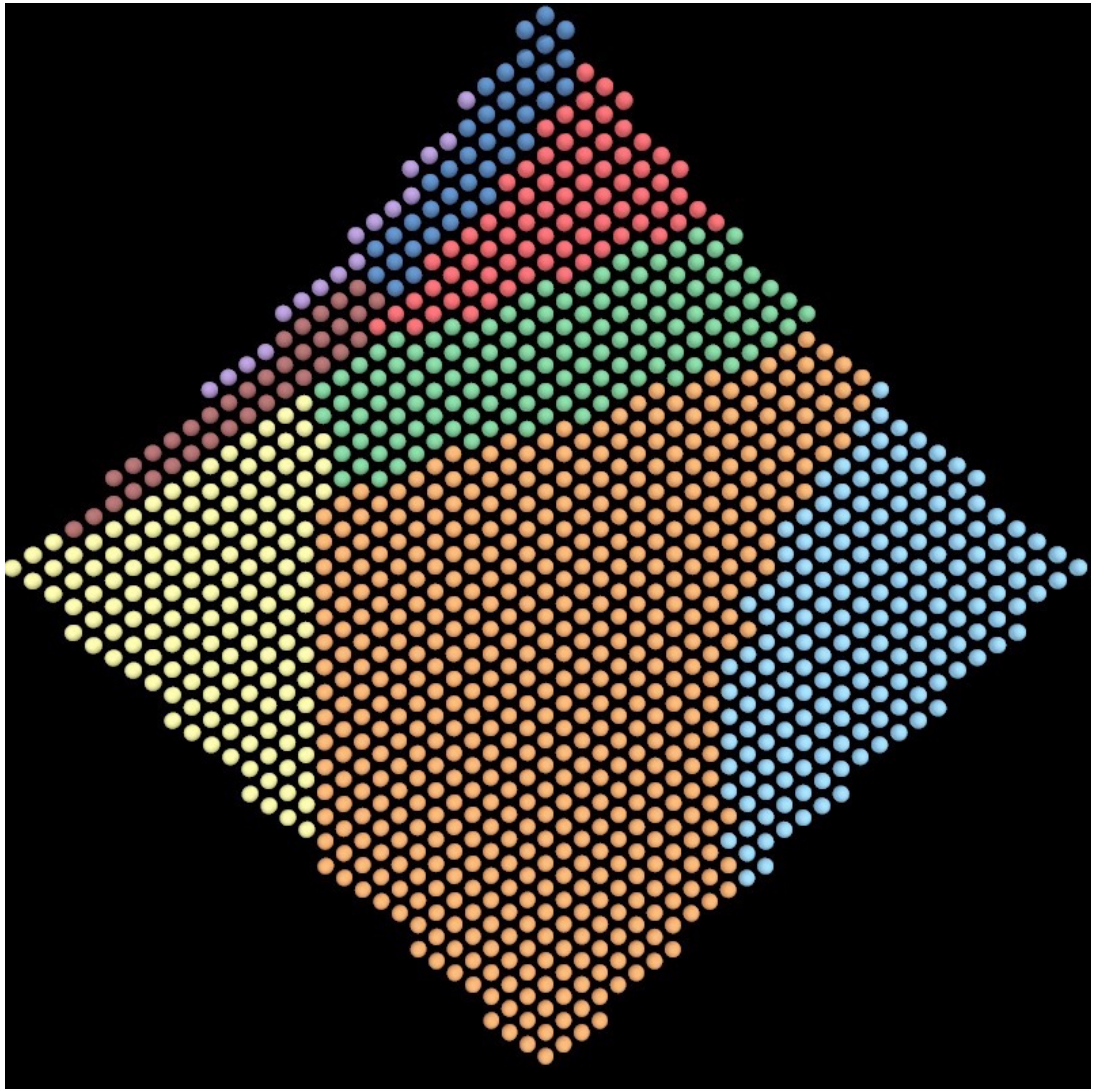
0. Determine the centroid of each cluster (in 73-dimensional hyperspace).

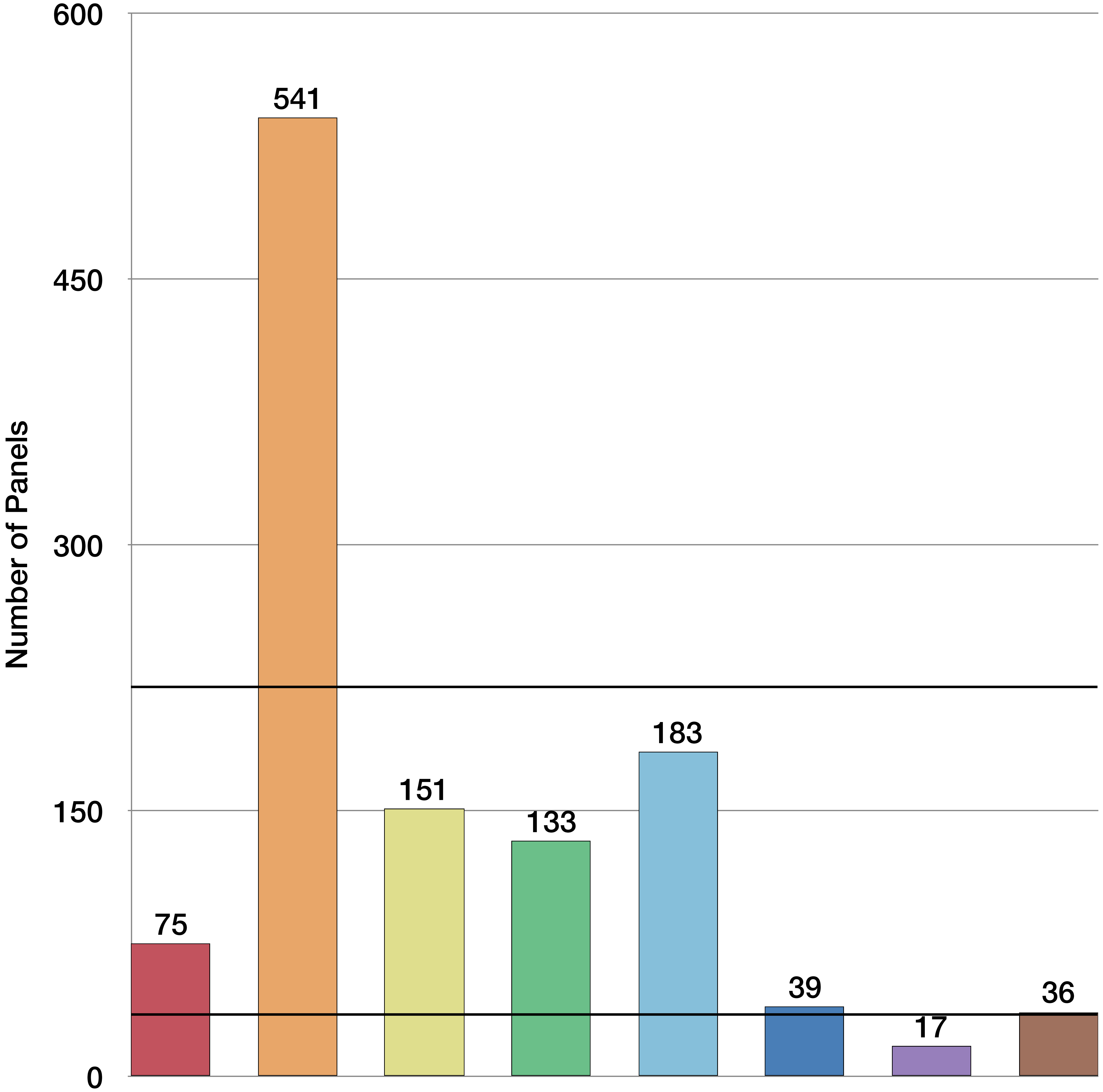
Repeat Steps 1-3

1. If a zone has more than 220 panels, move a panels furthest from the centroid to their next closest cluster.
2. Recompute cluster centroids
3. Put all panels in the cluster with the closest centroid

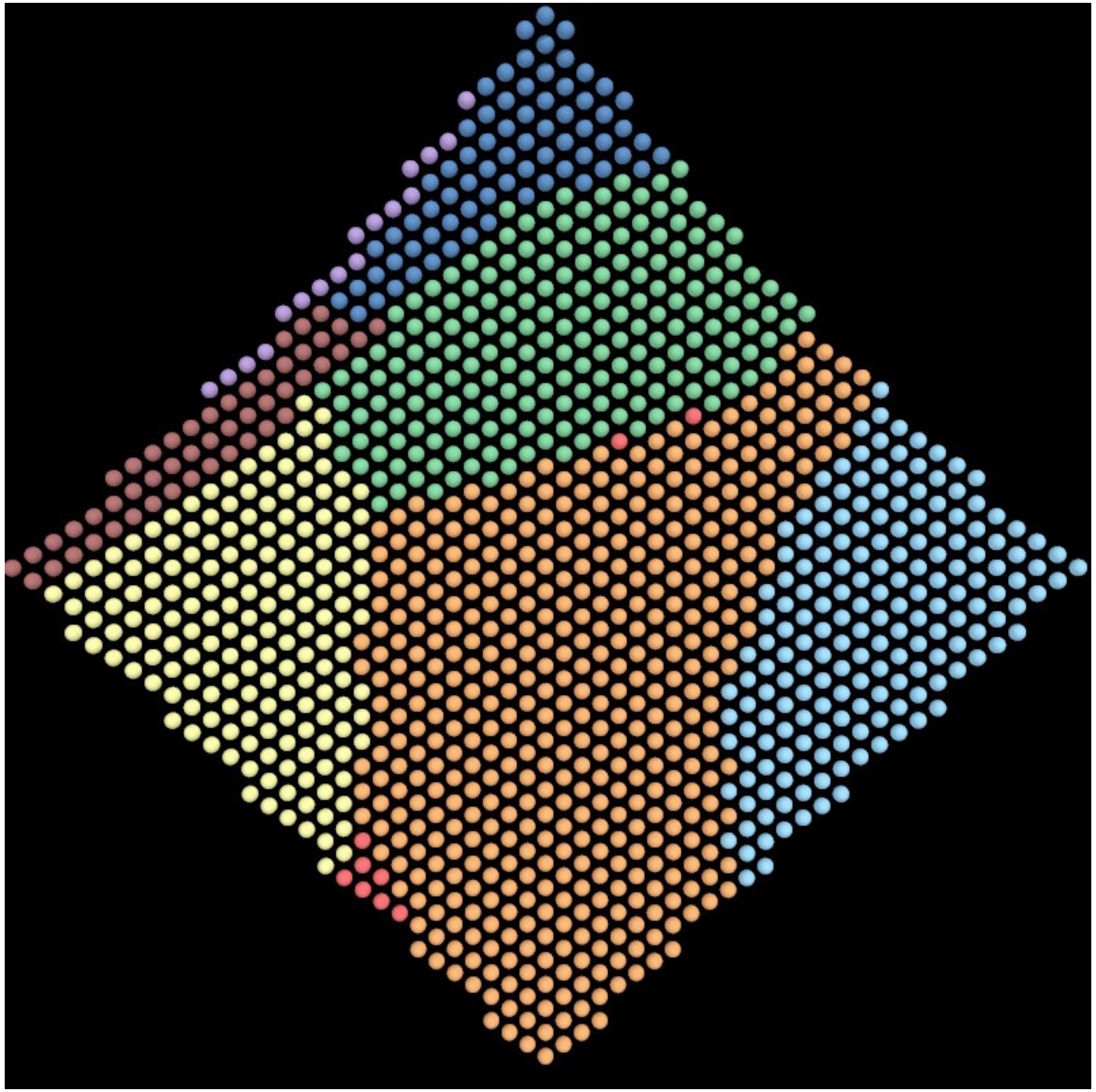
Iterative Reassignment in Action

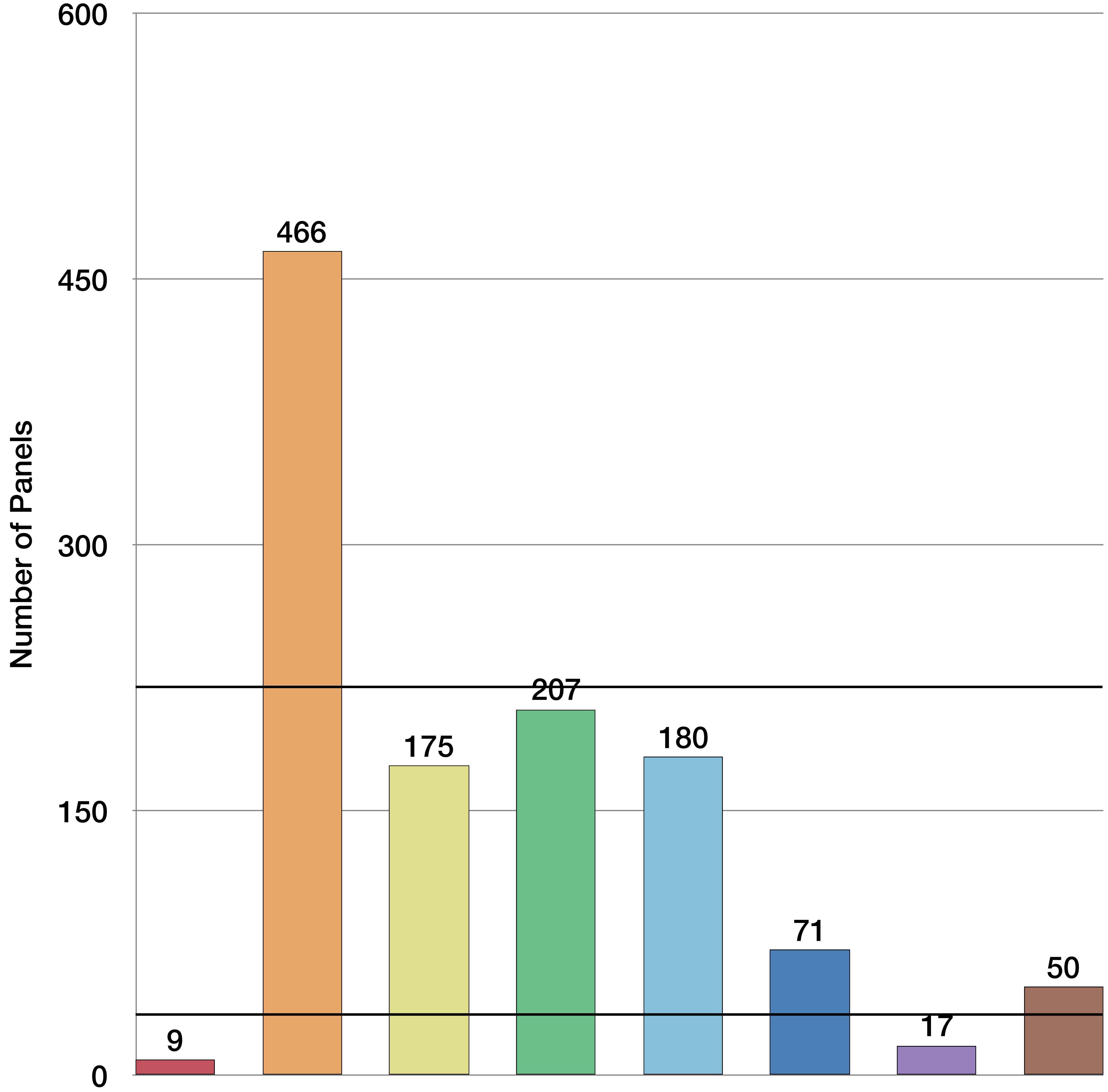
Clustering Result - Bay 05



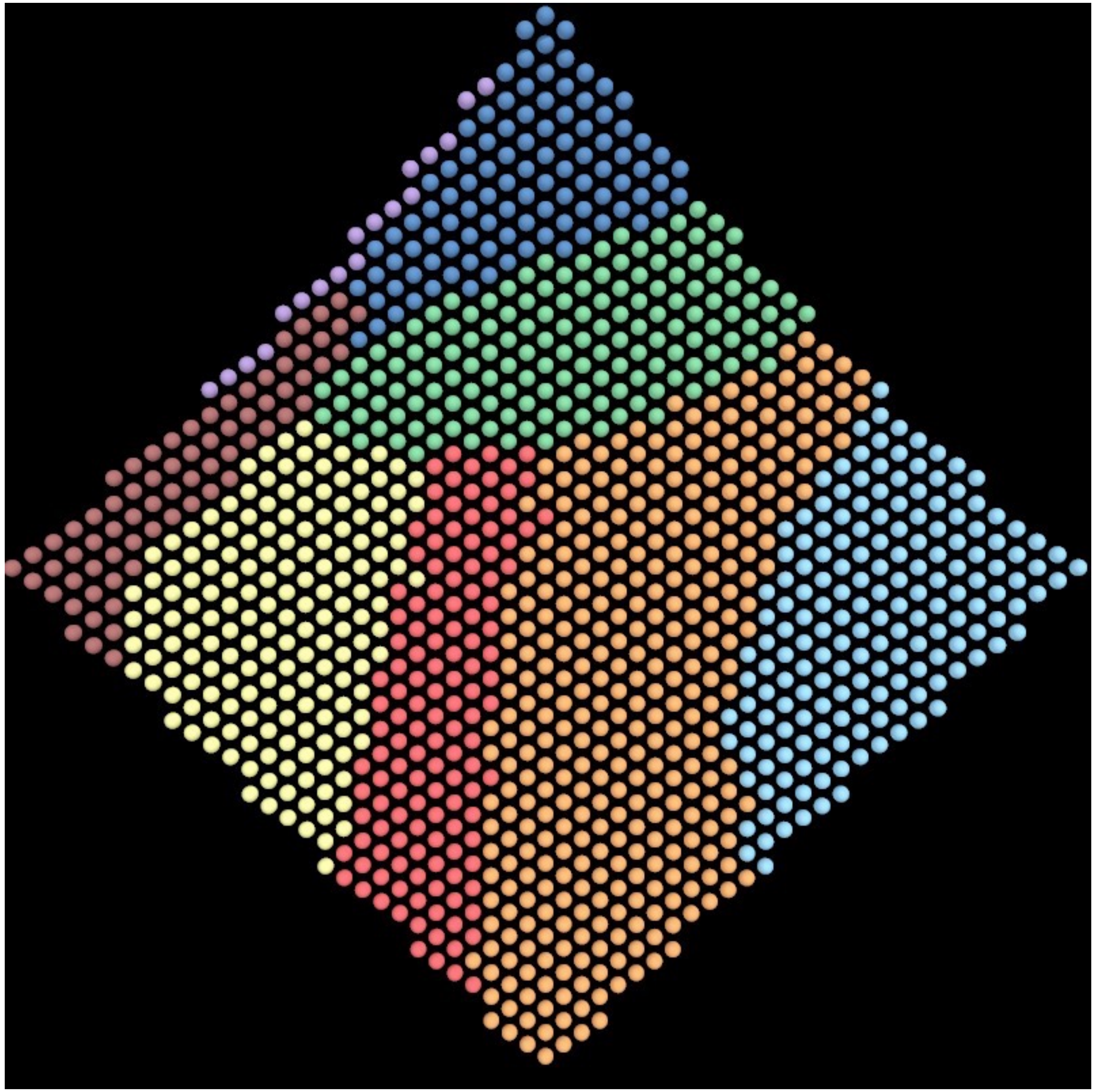


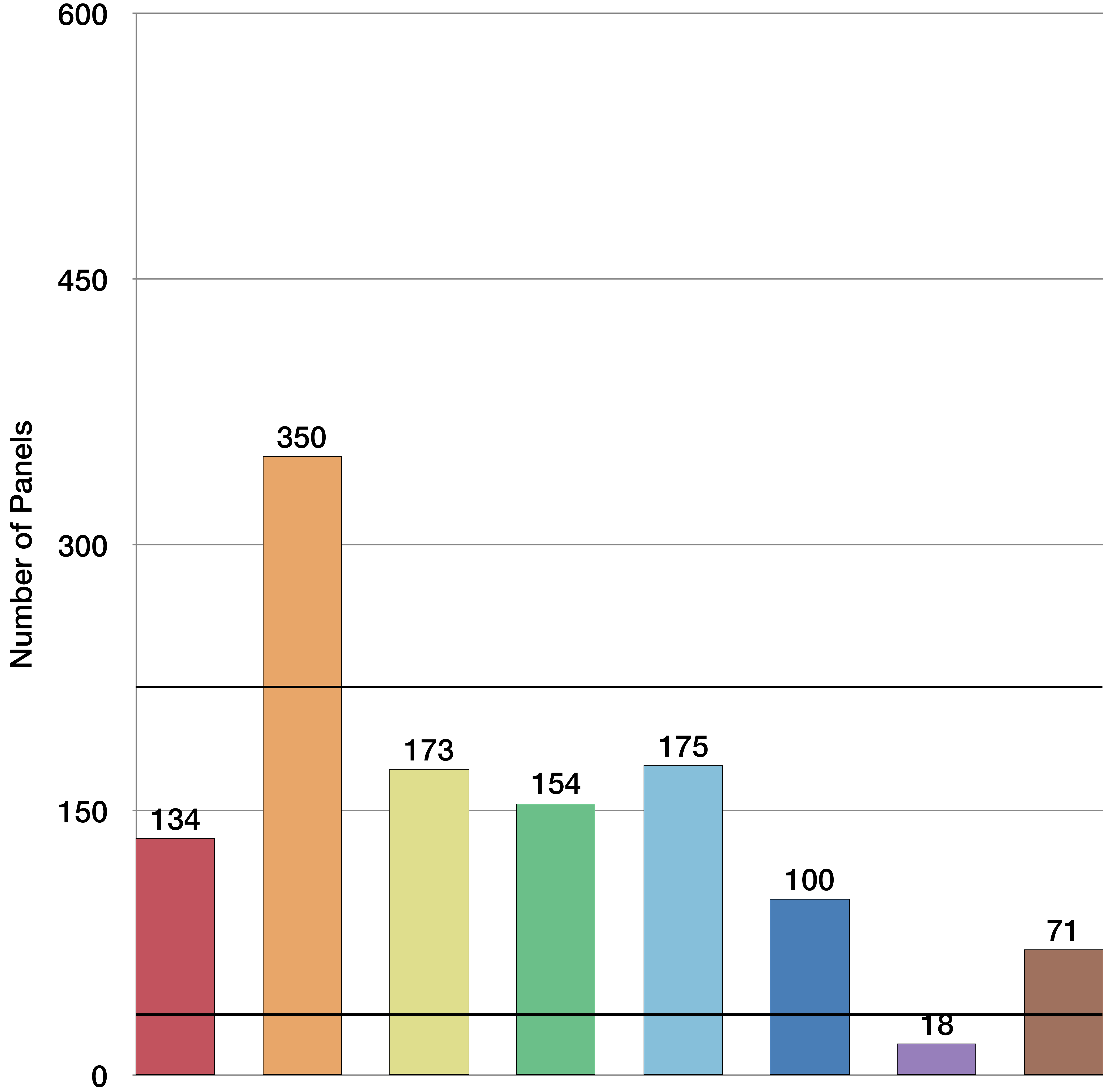
Iterative Reassignment - Iteration 01



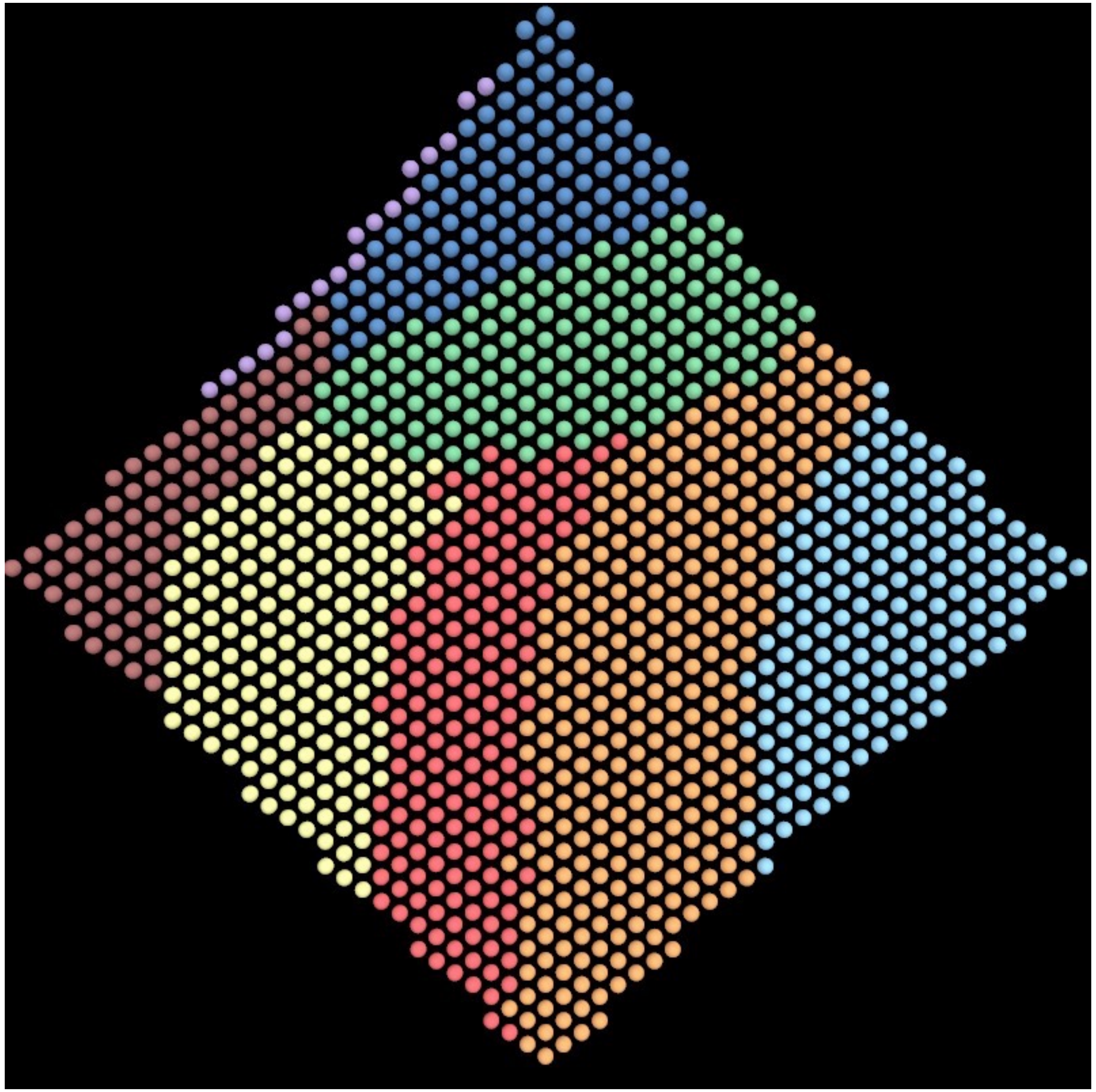


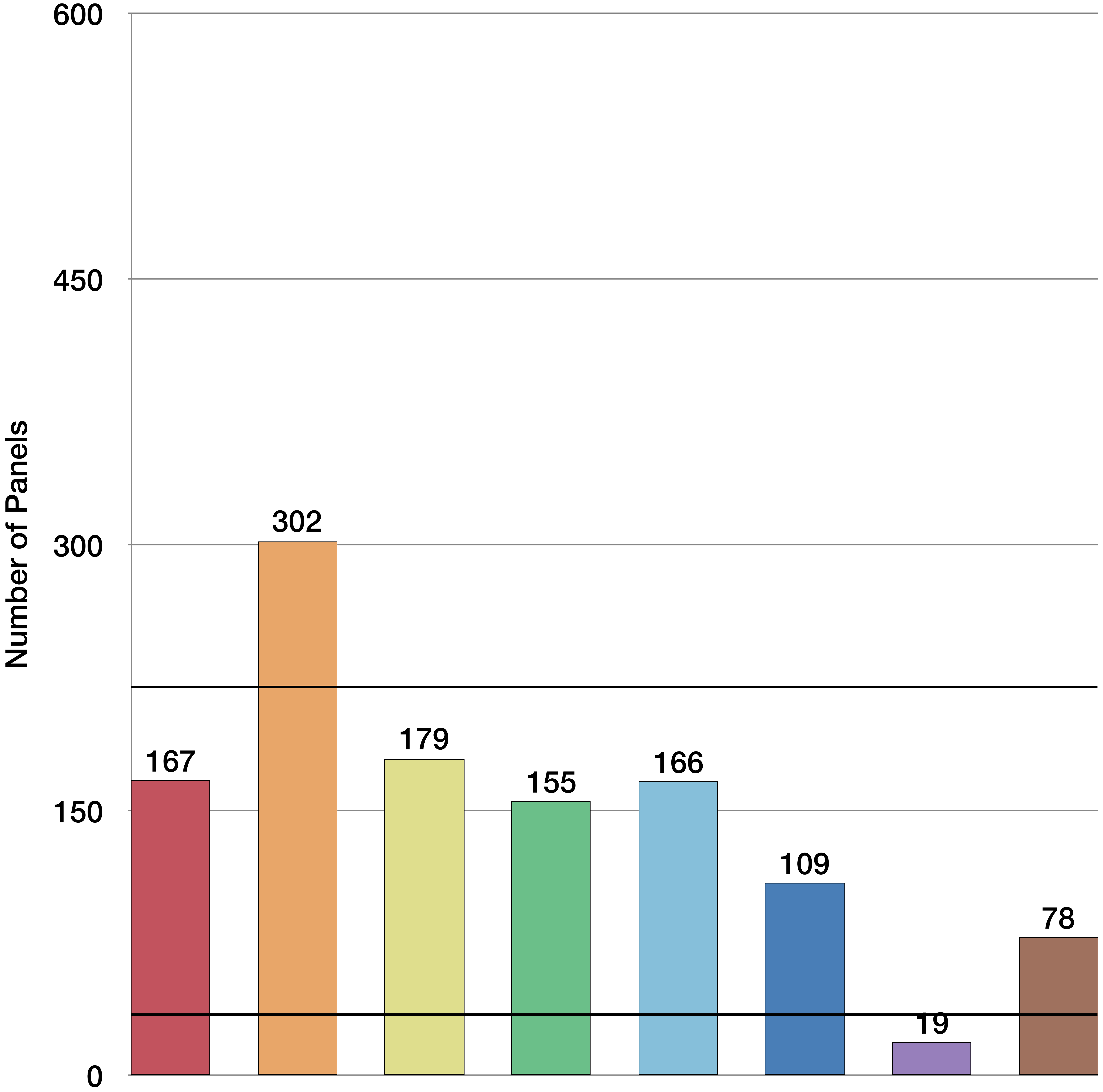
Iterative Reassignment - Iteration 02





Iterative Reassignment - Iteration 03





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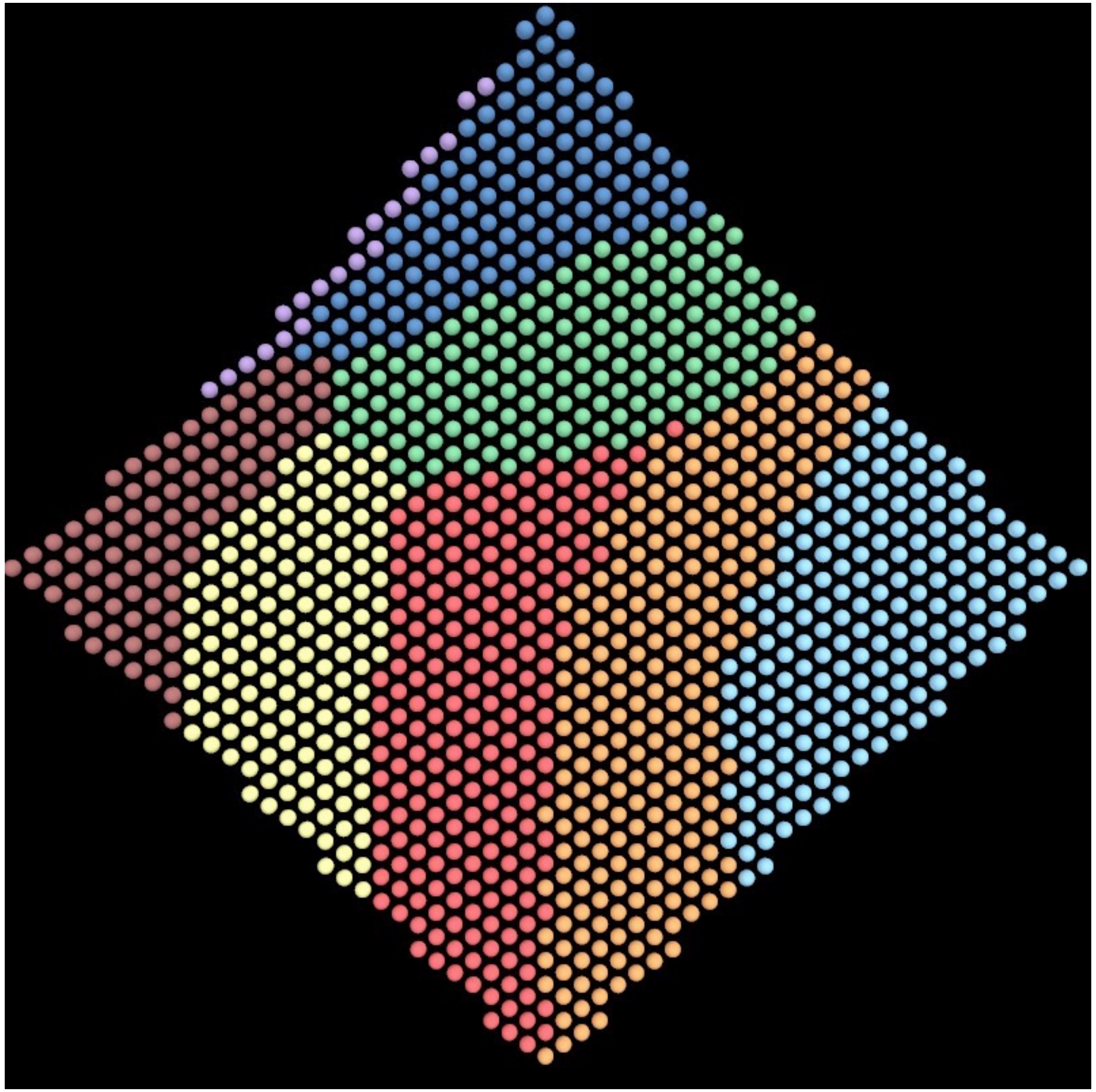
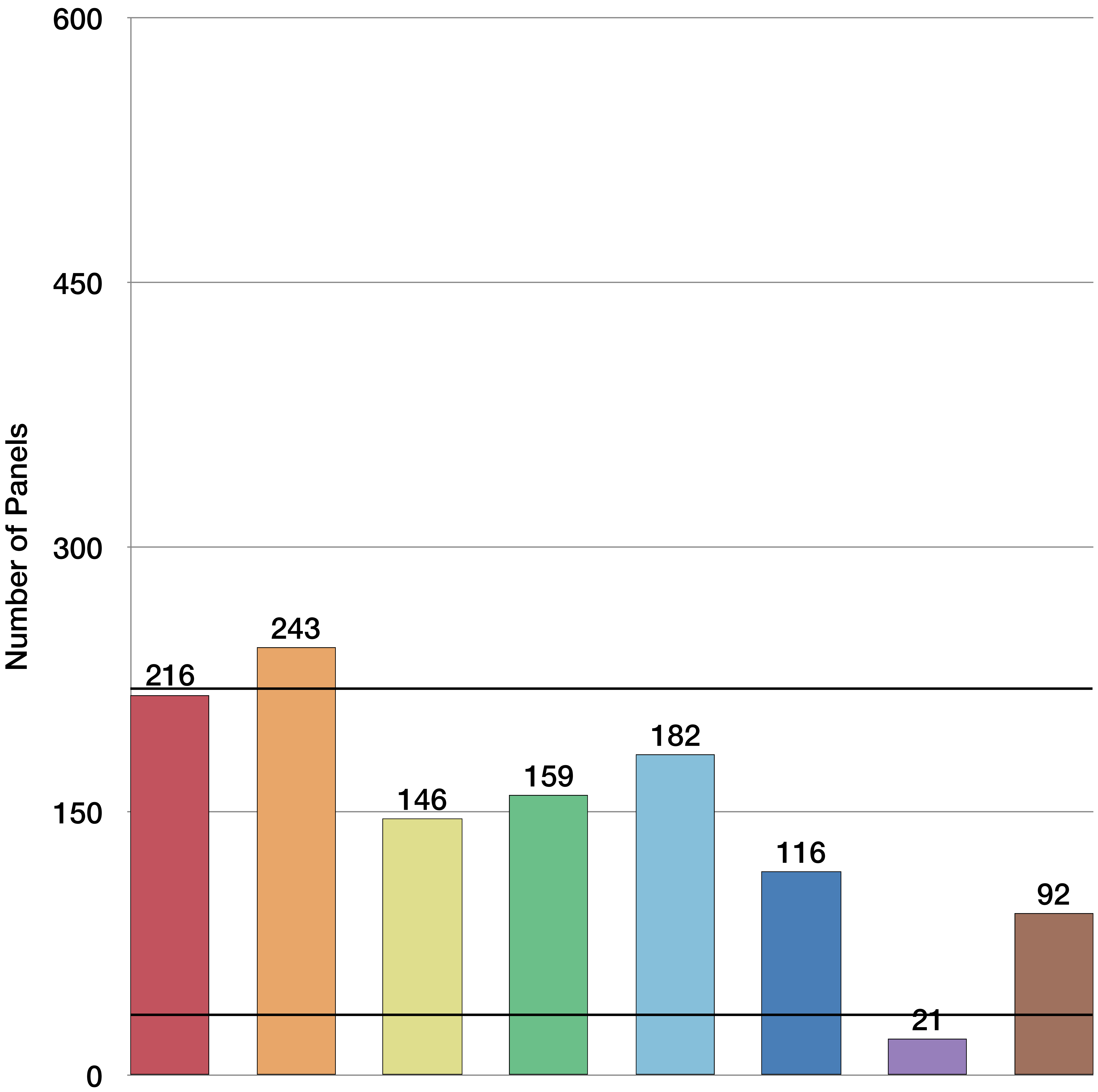
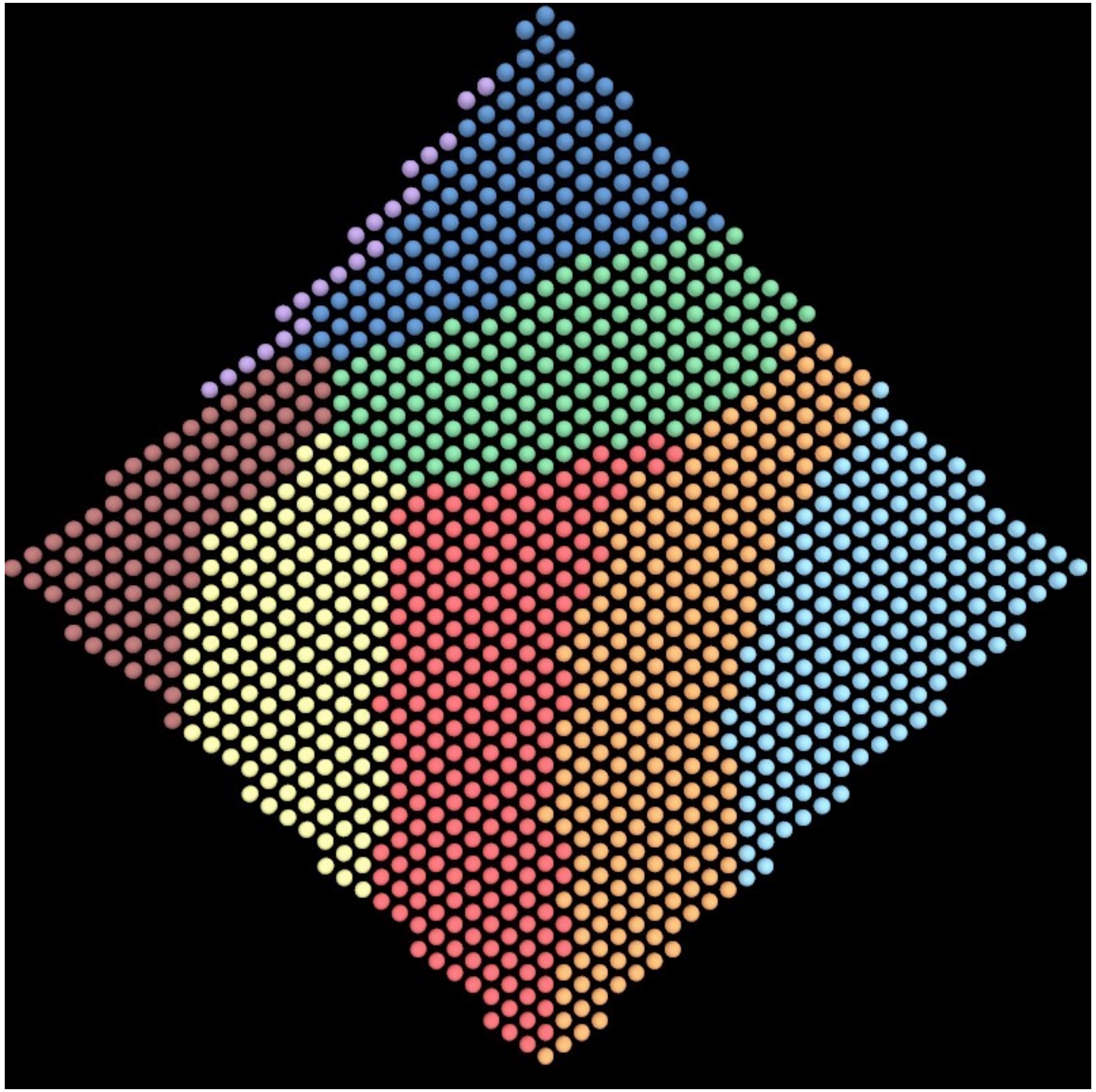
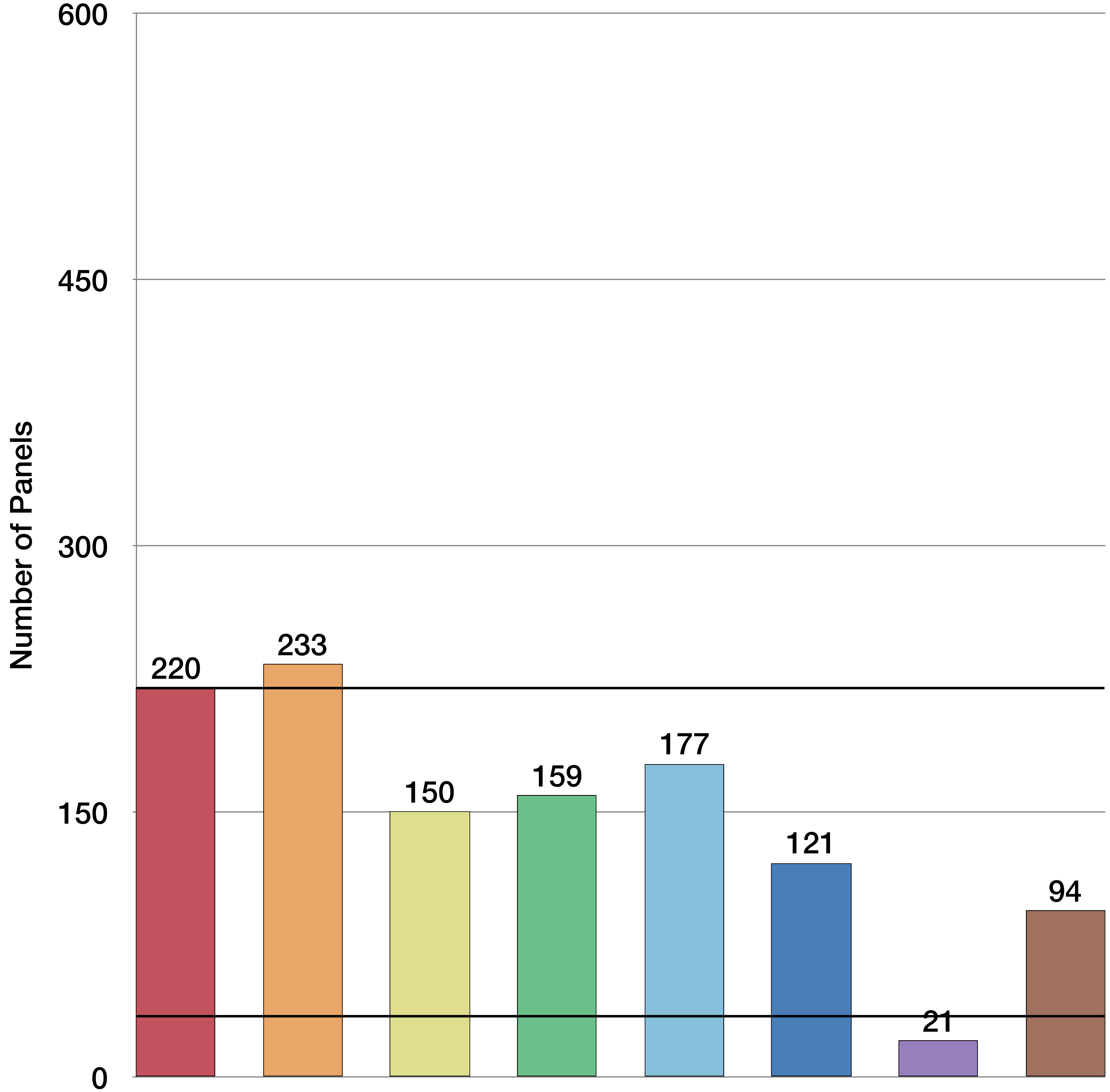


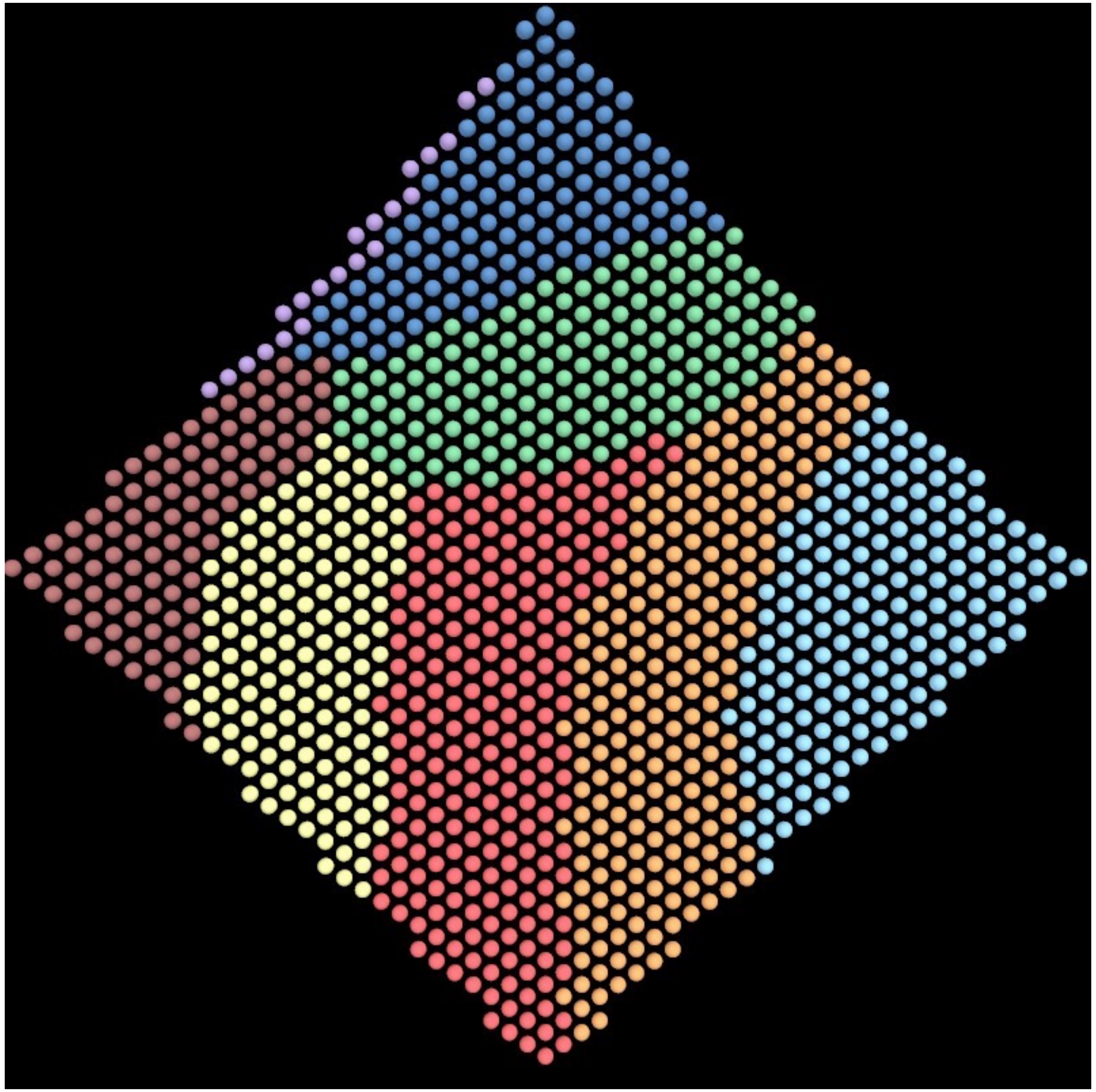


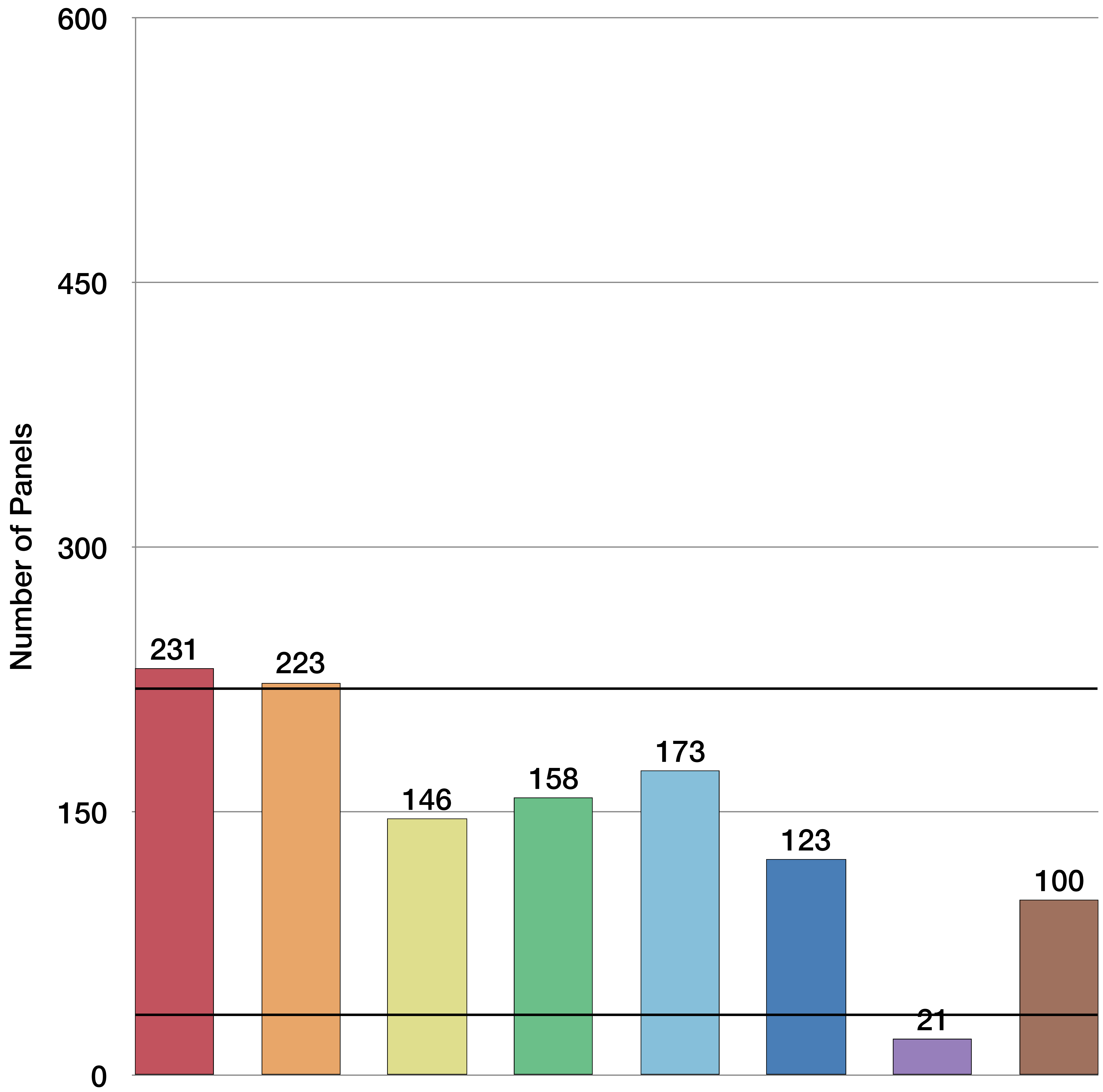
Iterative Reassignment - Iteration 05



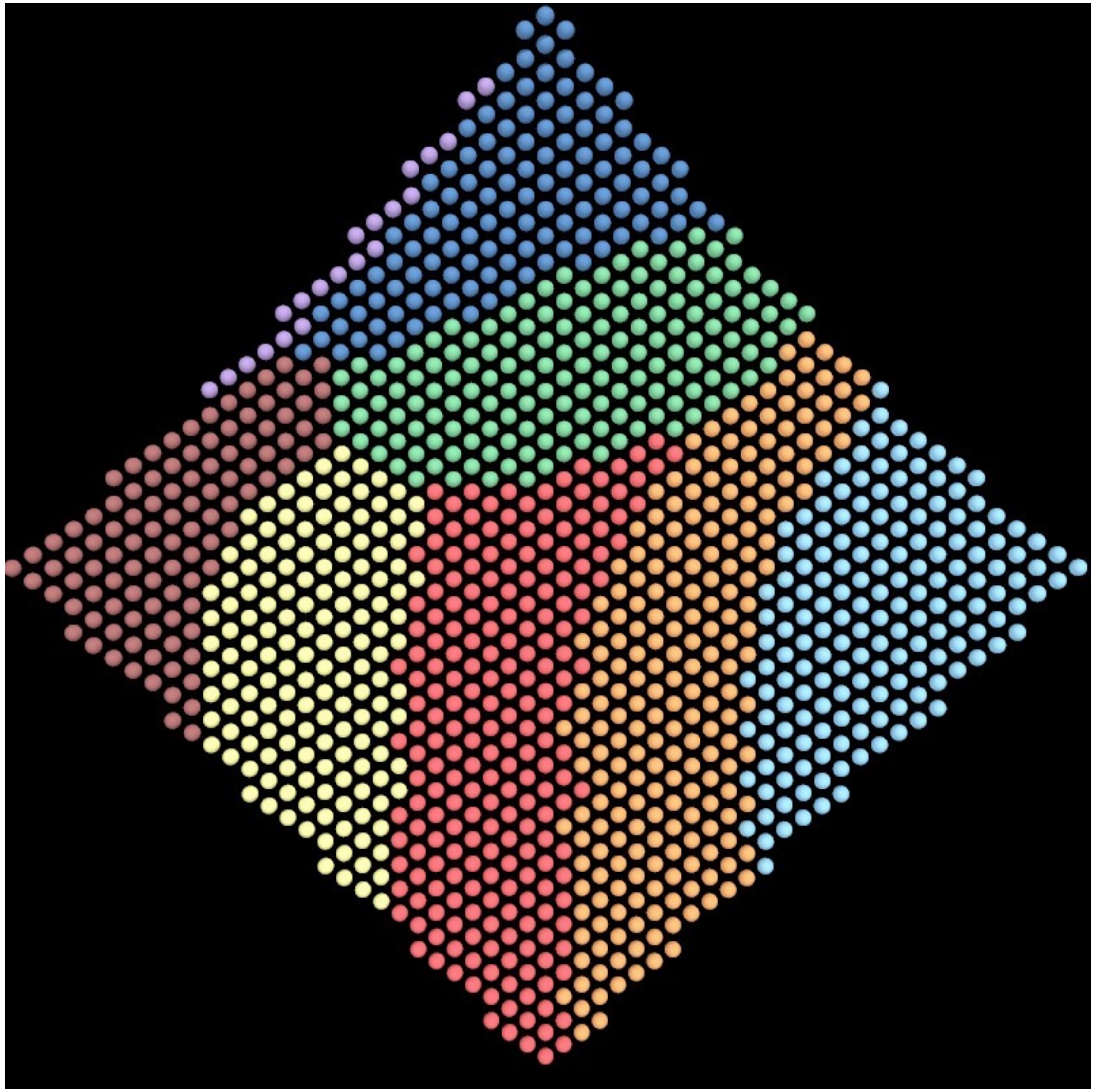


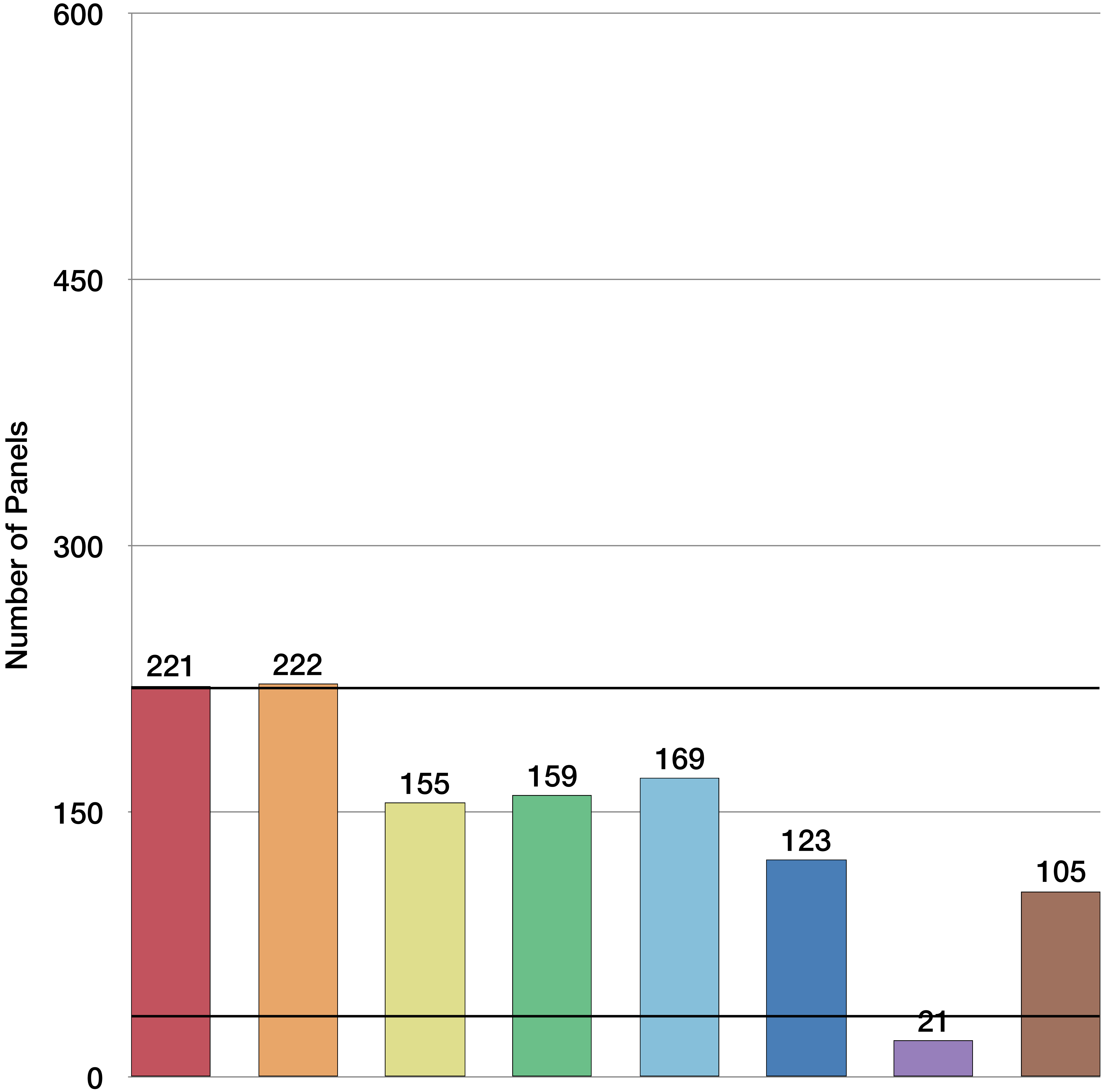
Iterative Reassignment - Iteration 06



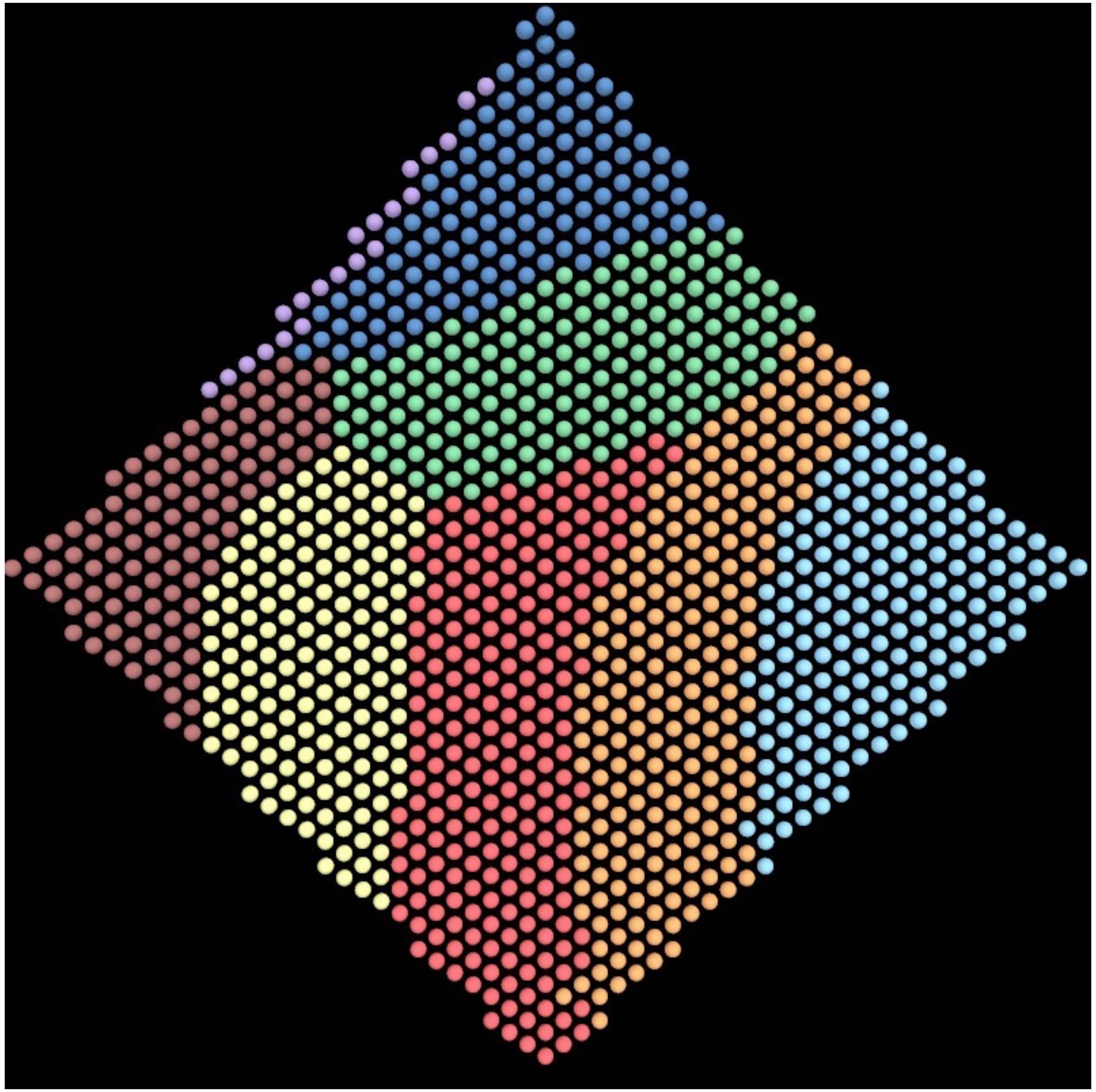


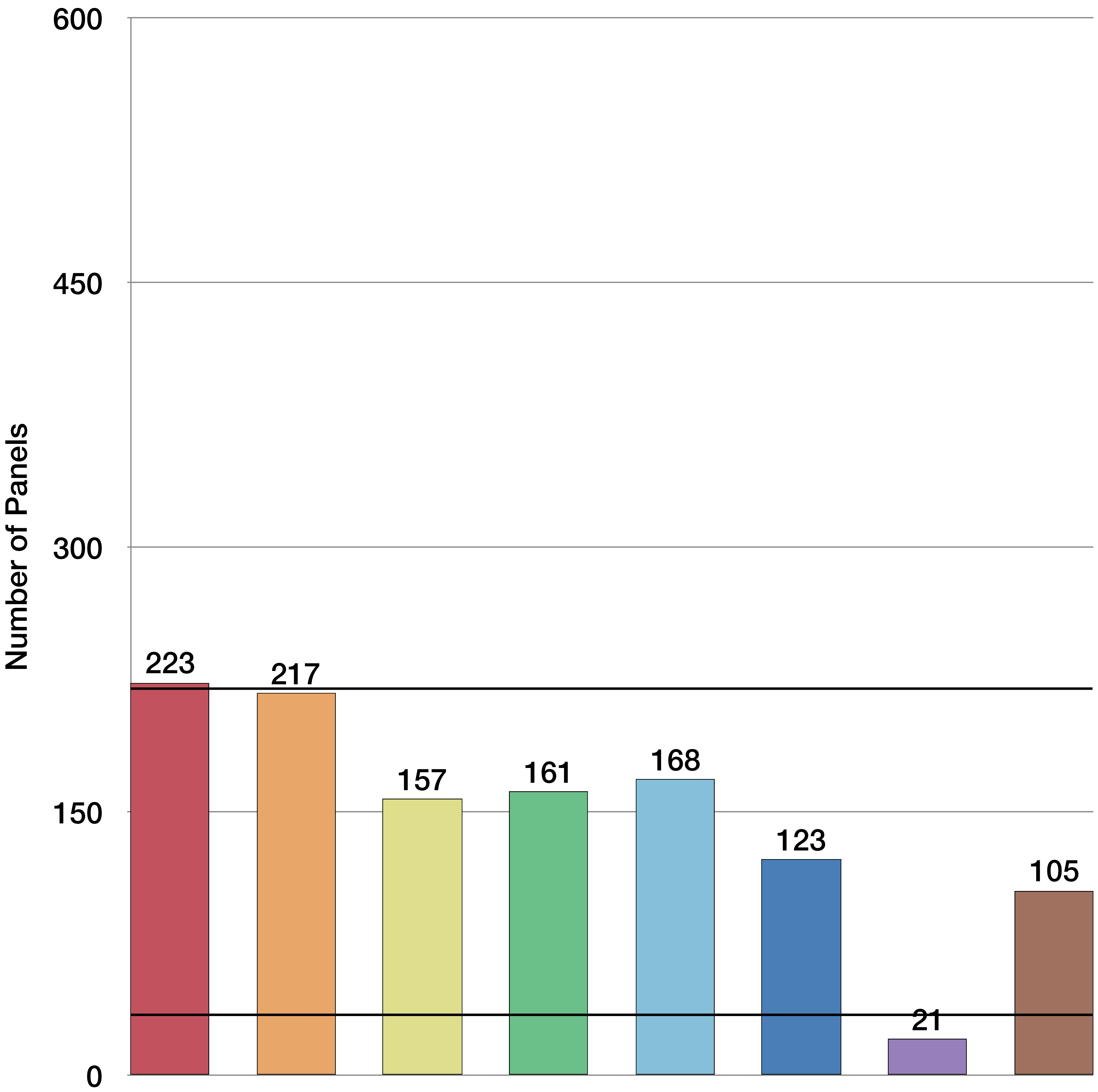
Iterative Reassignment - Iteration 07



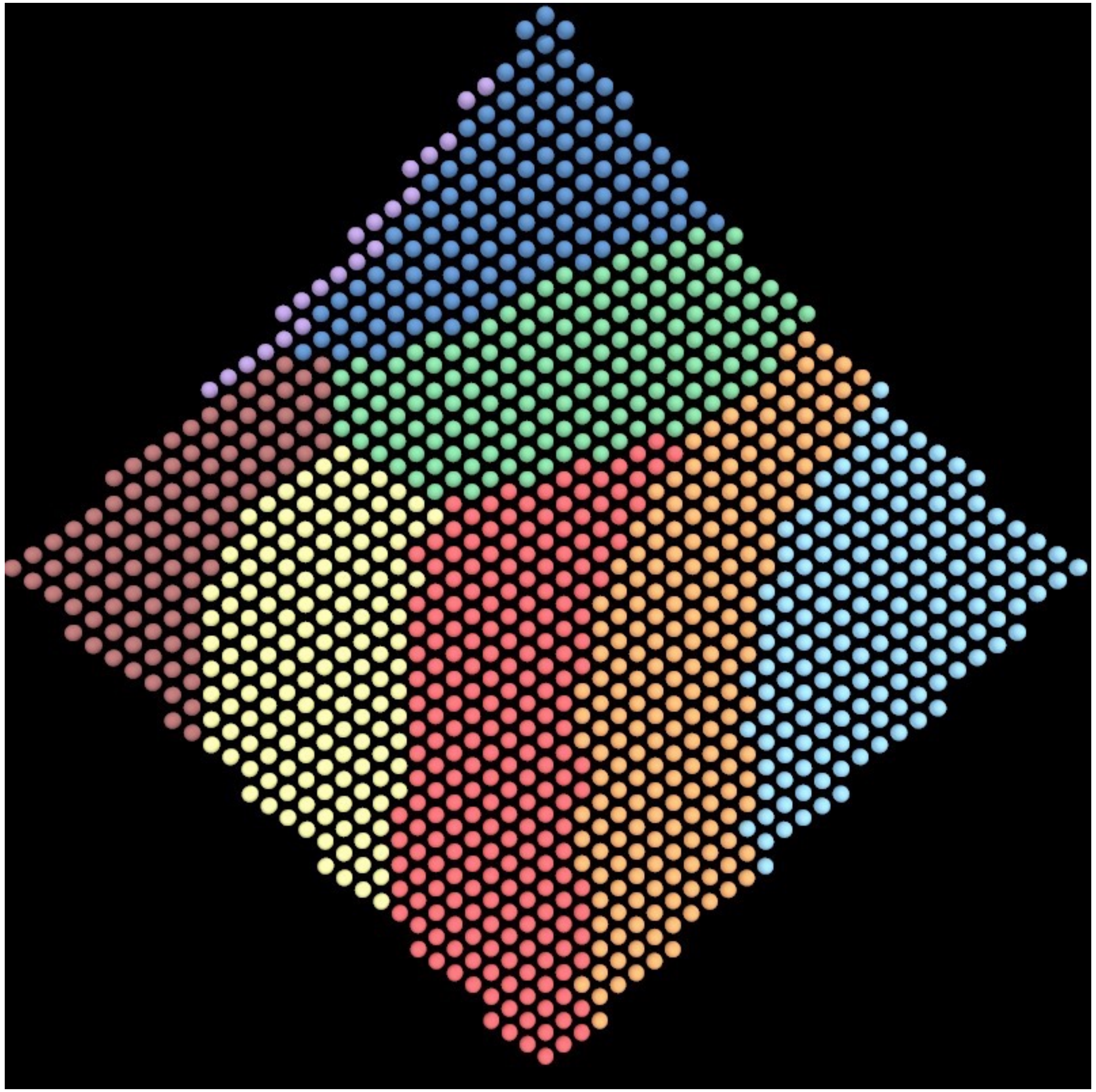


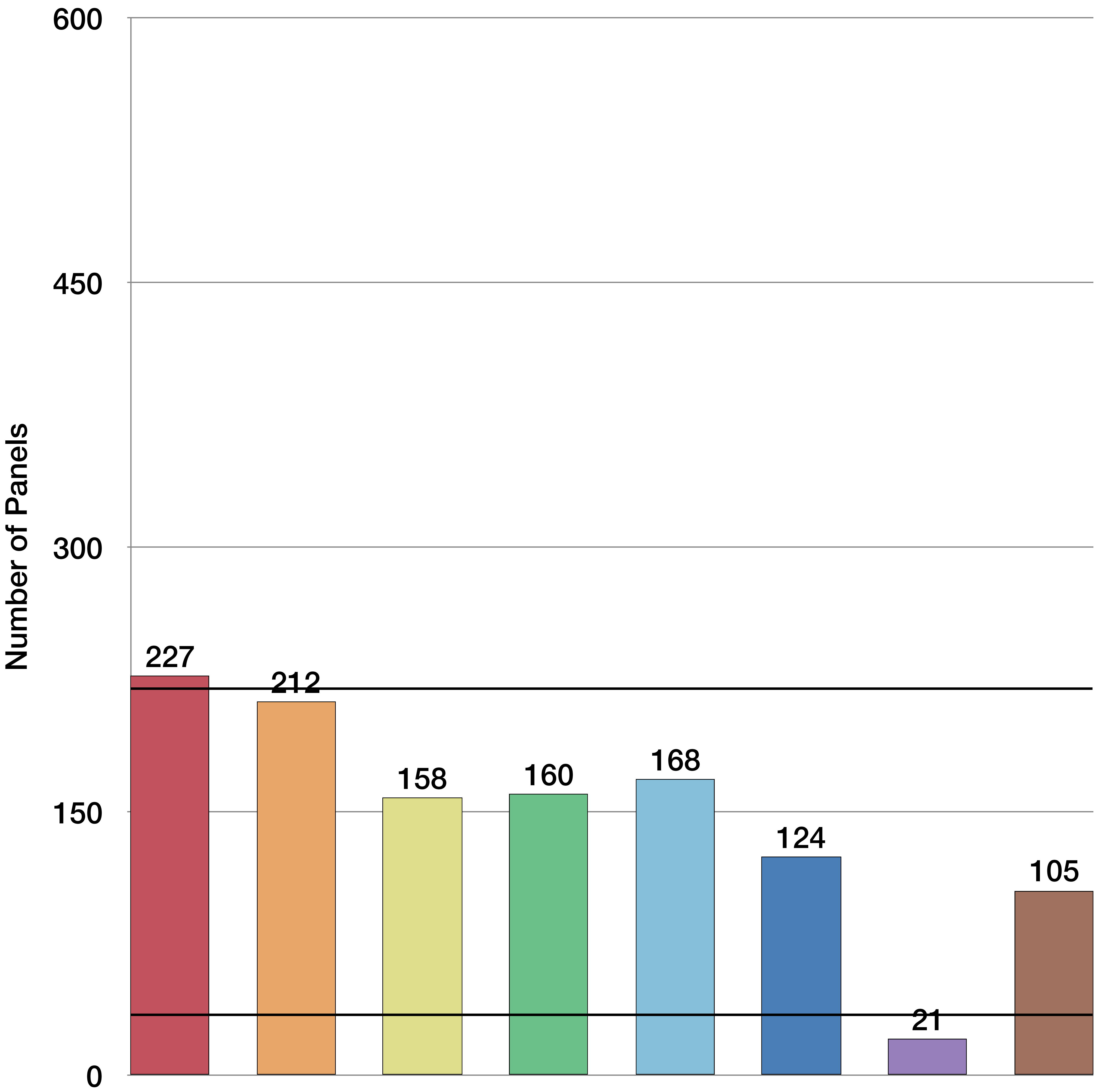
Iterative Reassignment - Iteration 08



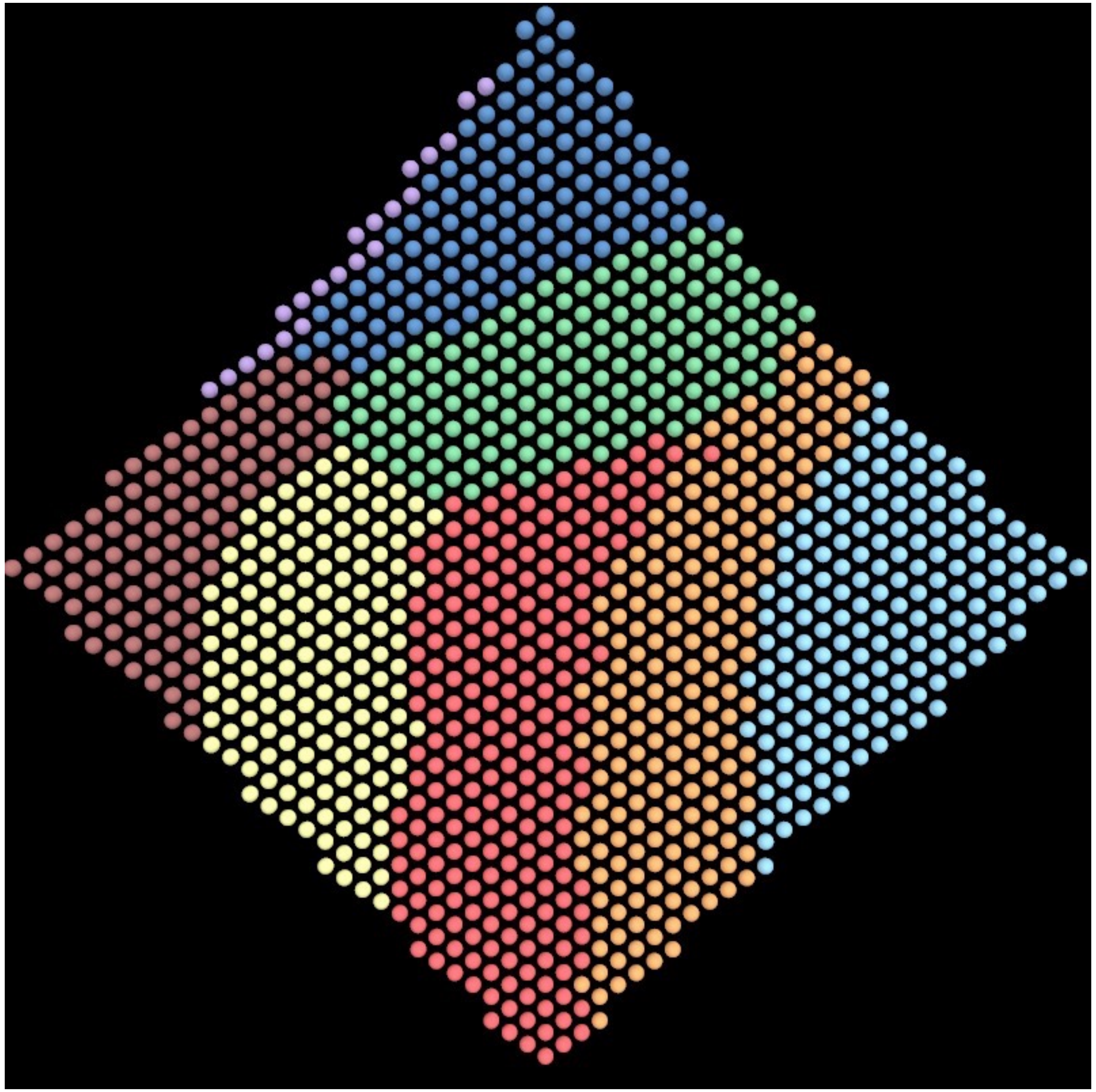


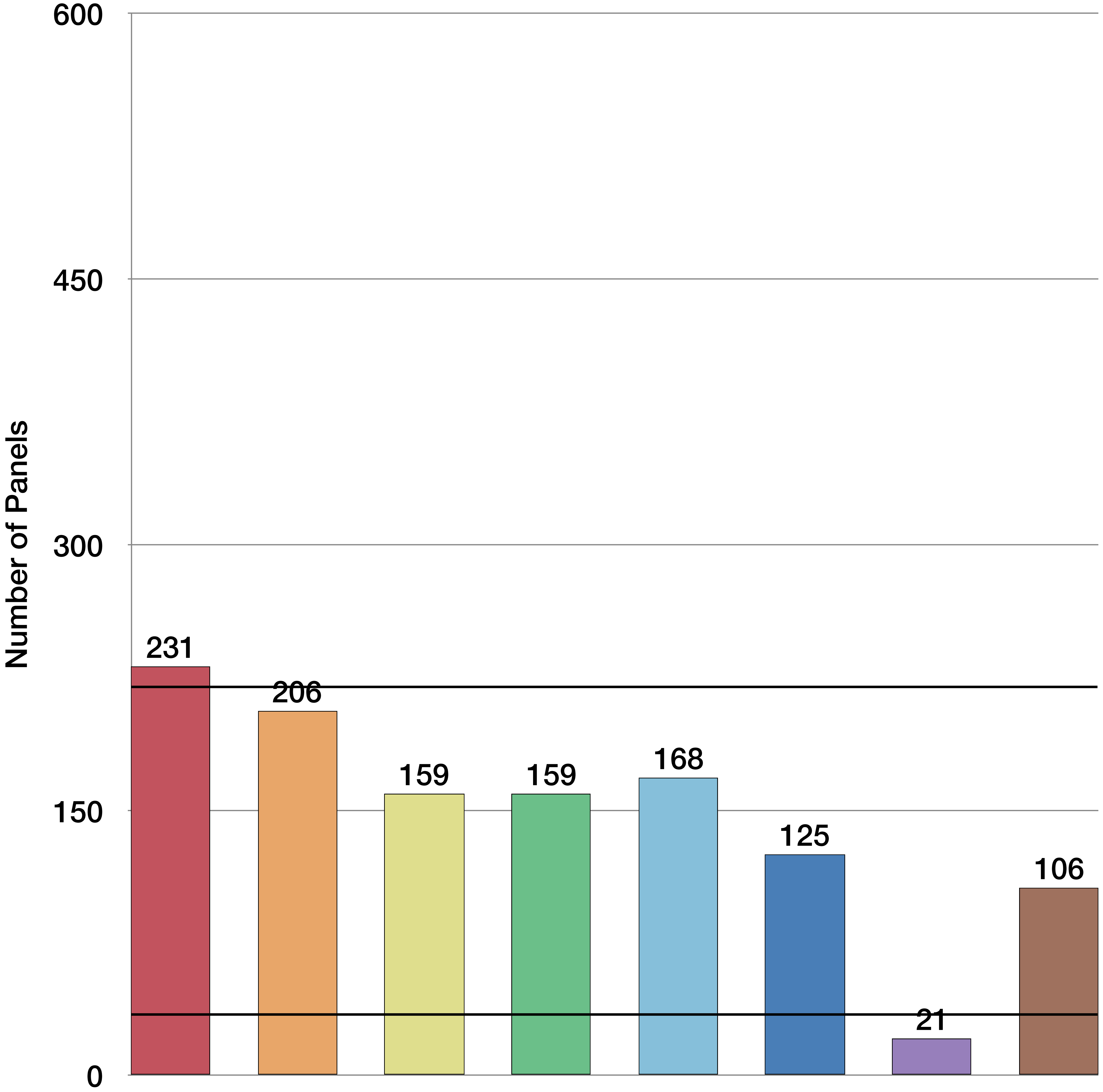
Iterative Reassignment - Iteration 09



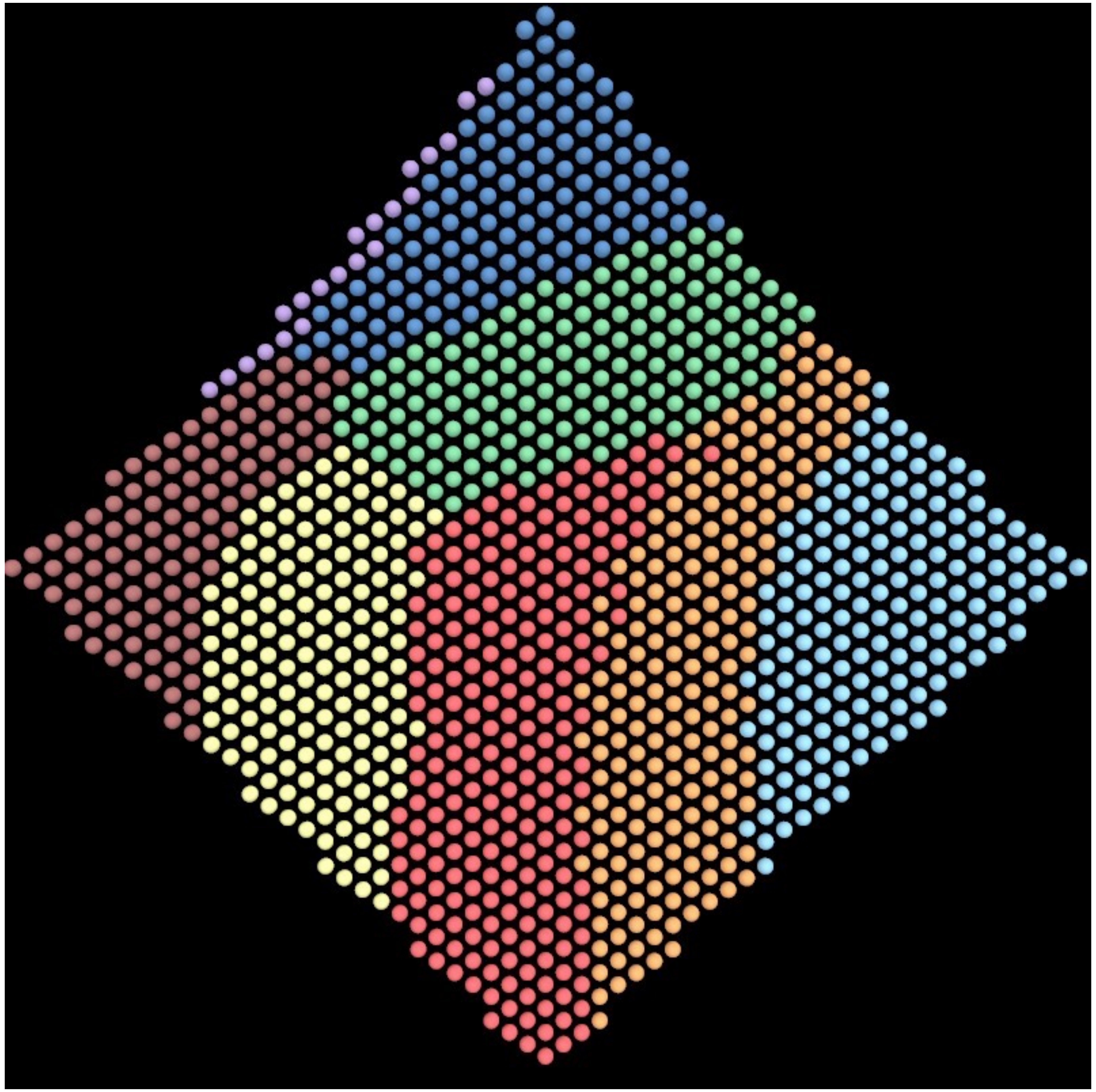


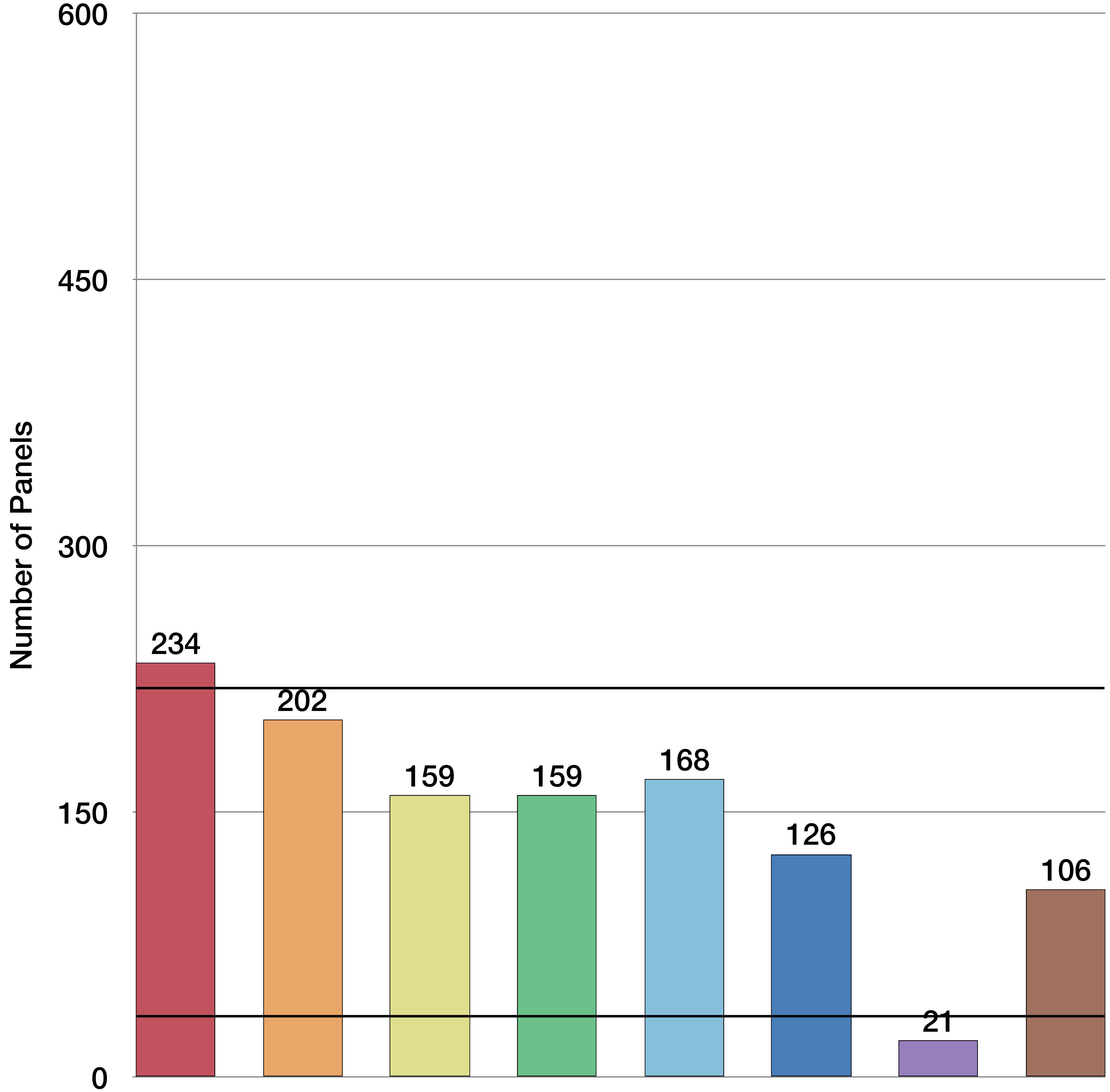
Iterative Reassignment - Iteration 10



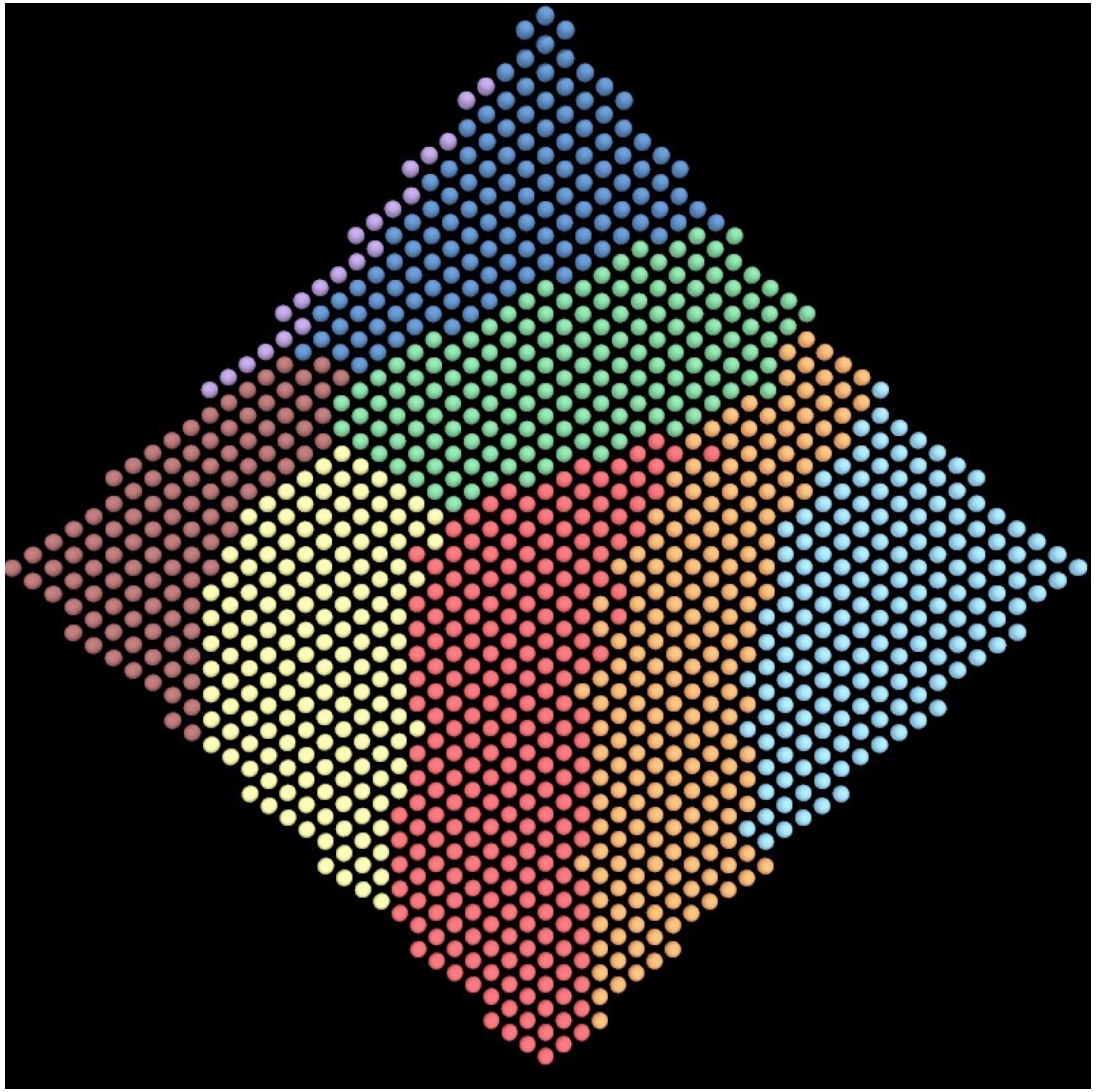


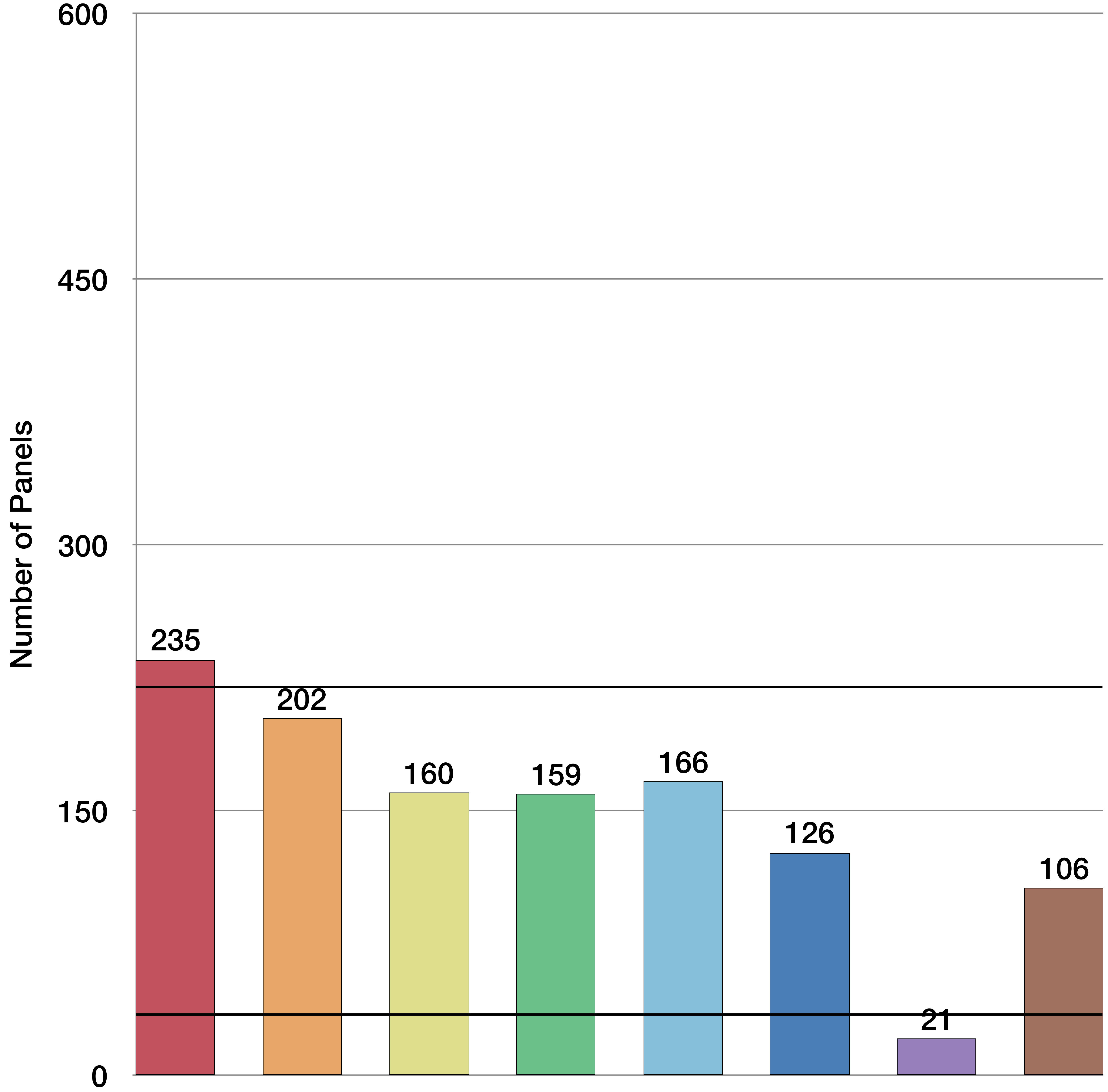
Iterative Reassignment - Iteration 11



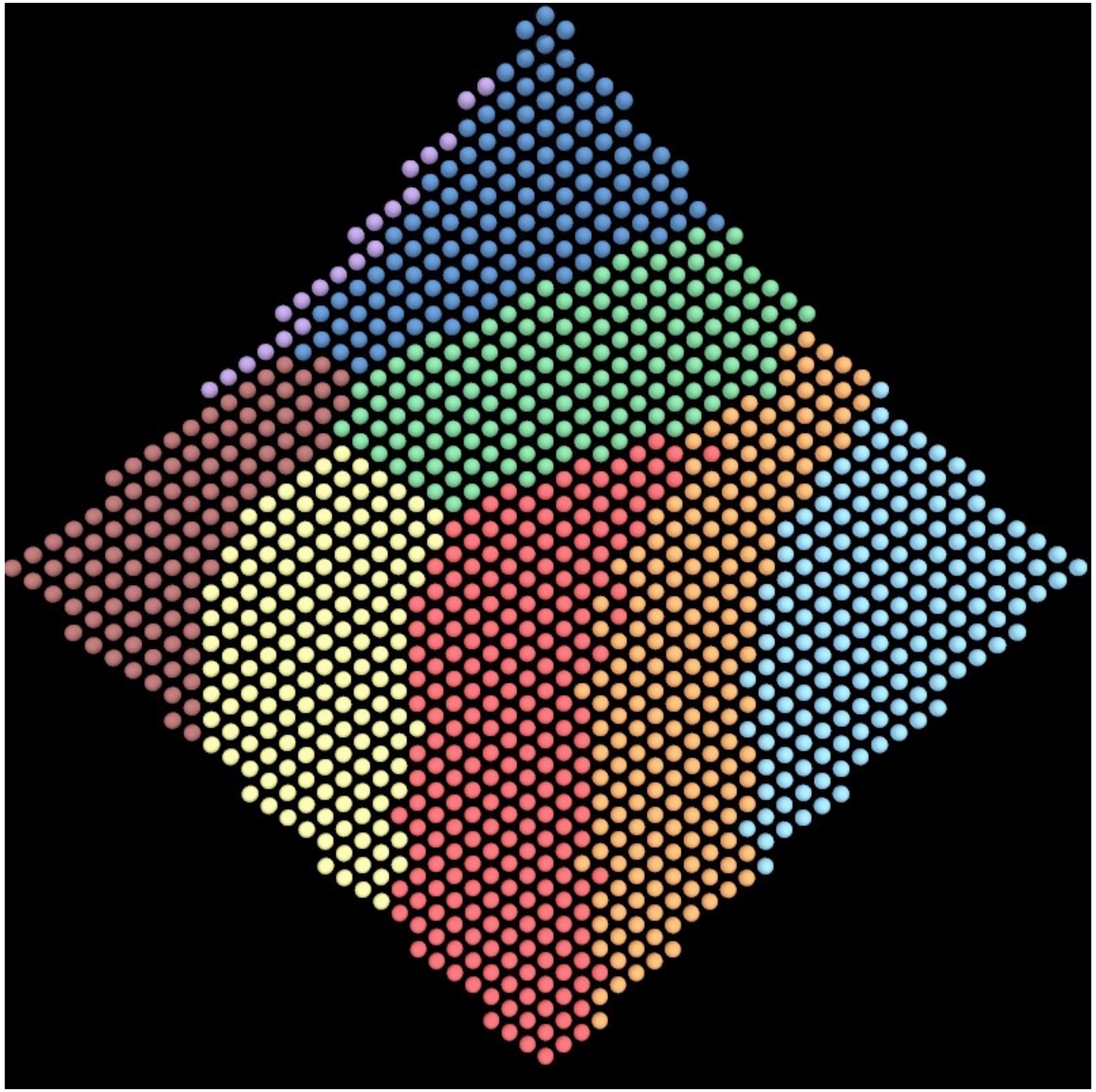


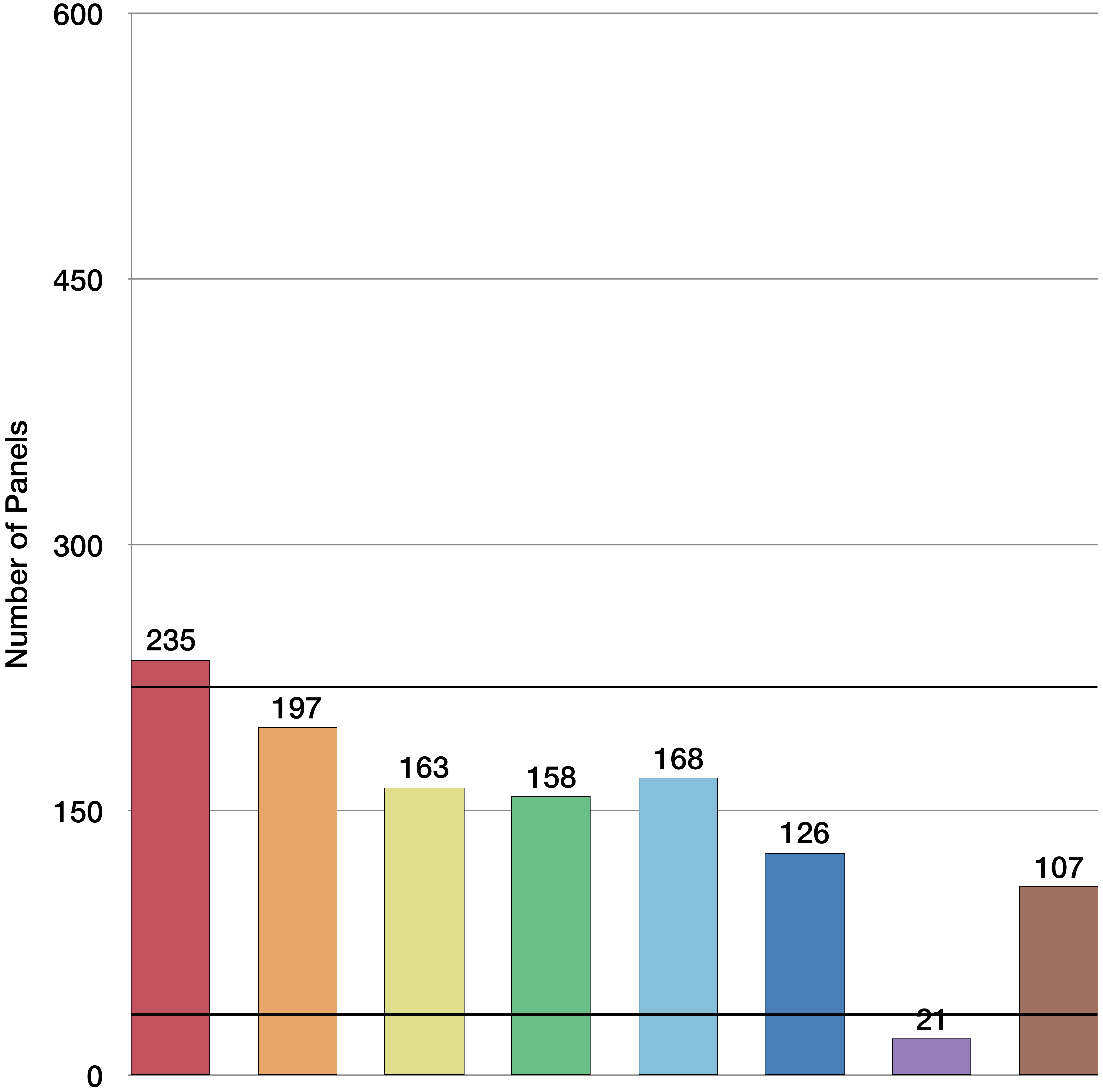
Iterative Reassignment - Iteration 12





Iterative Reassignment - Iteration 13





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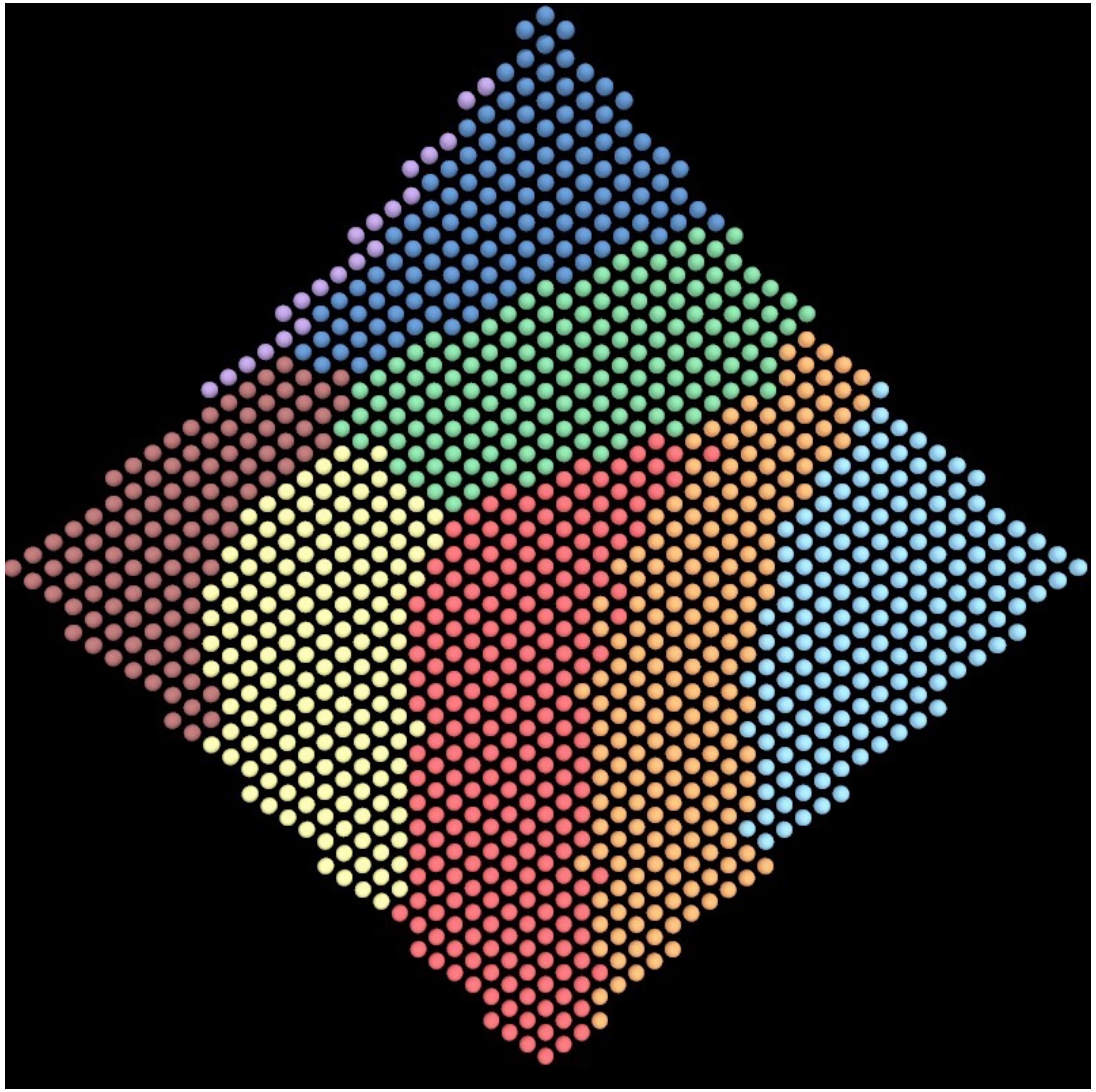
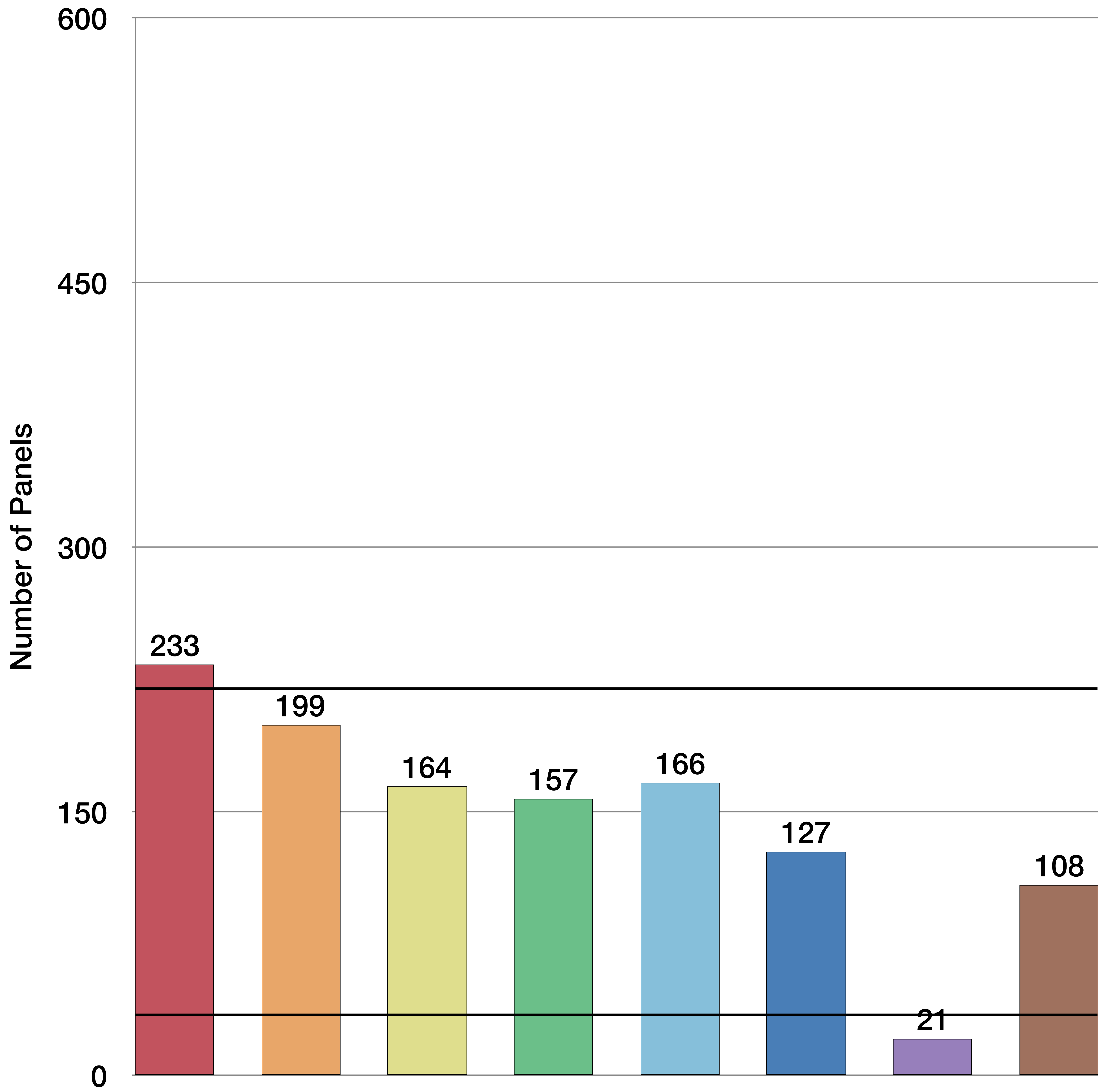
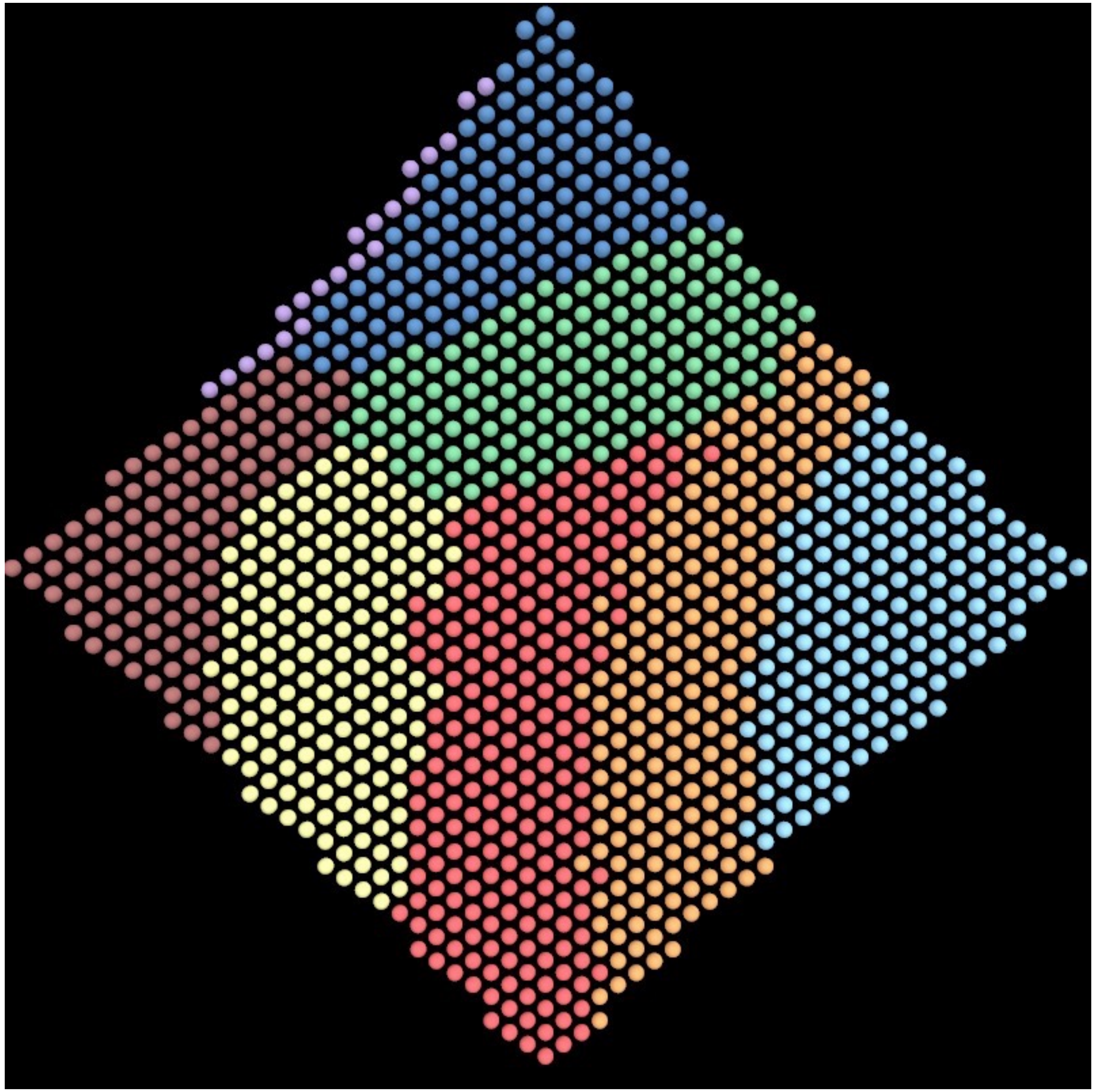
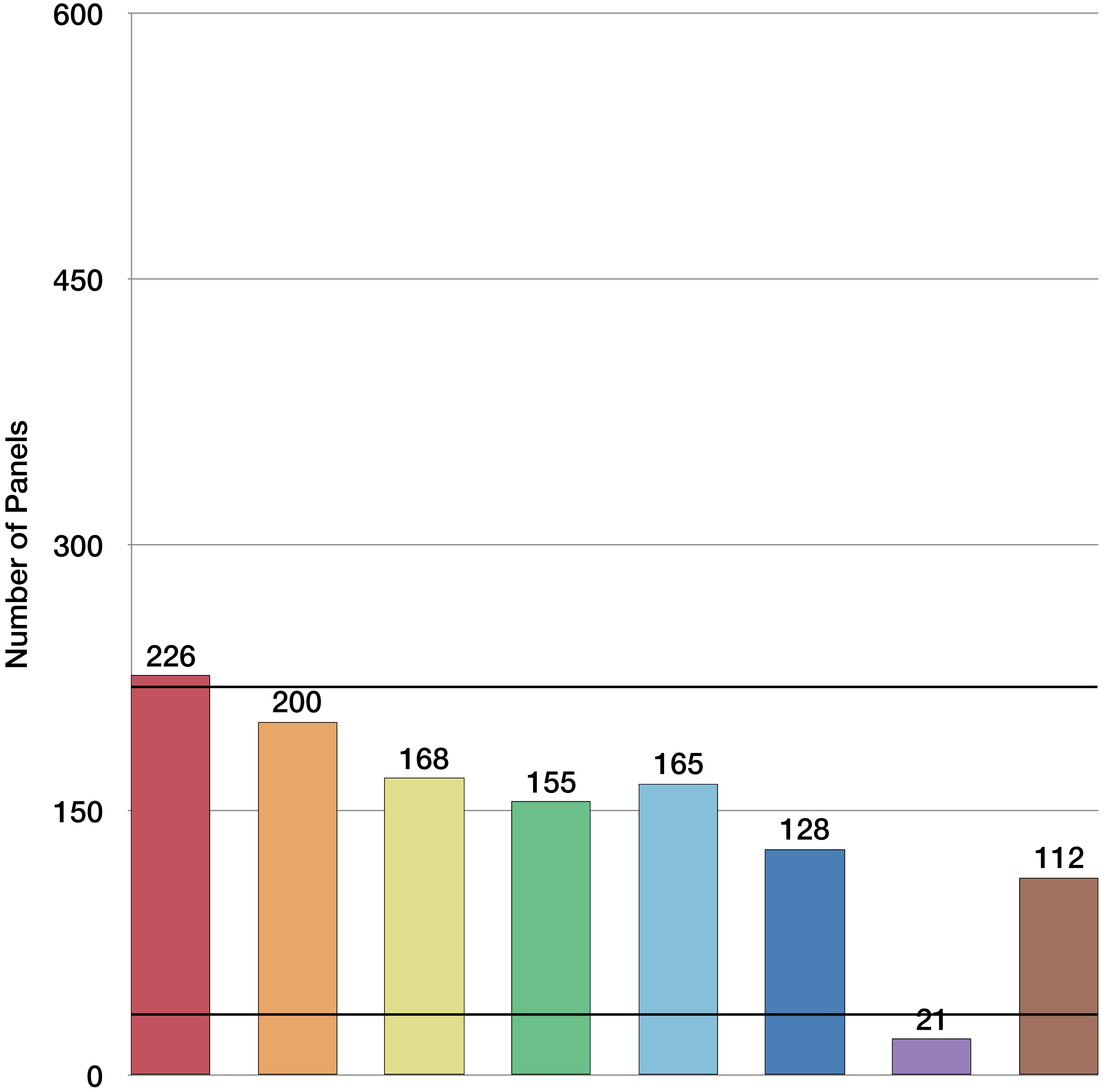


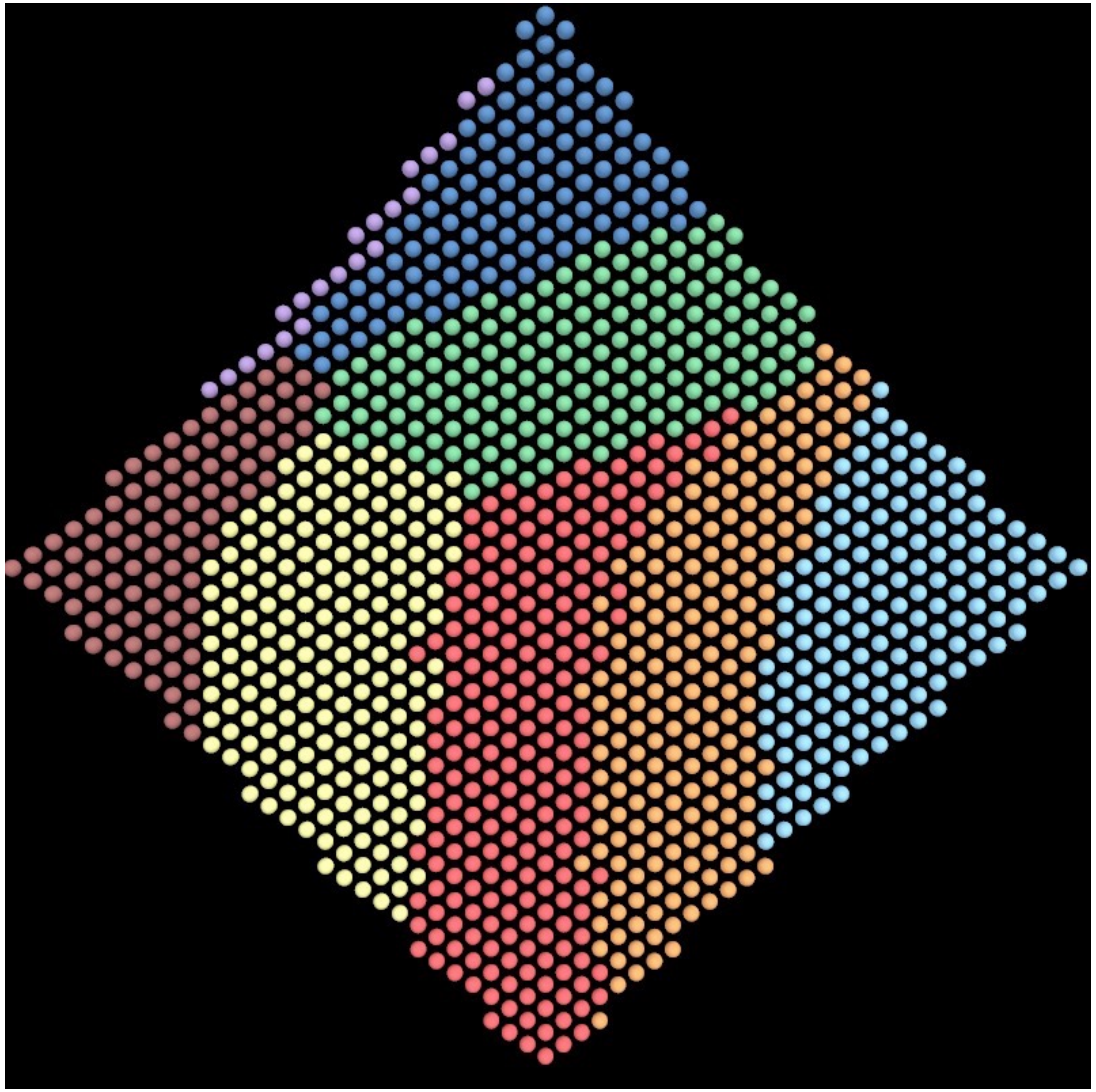


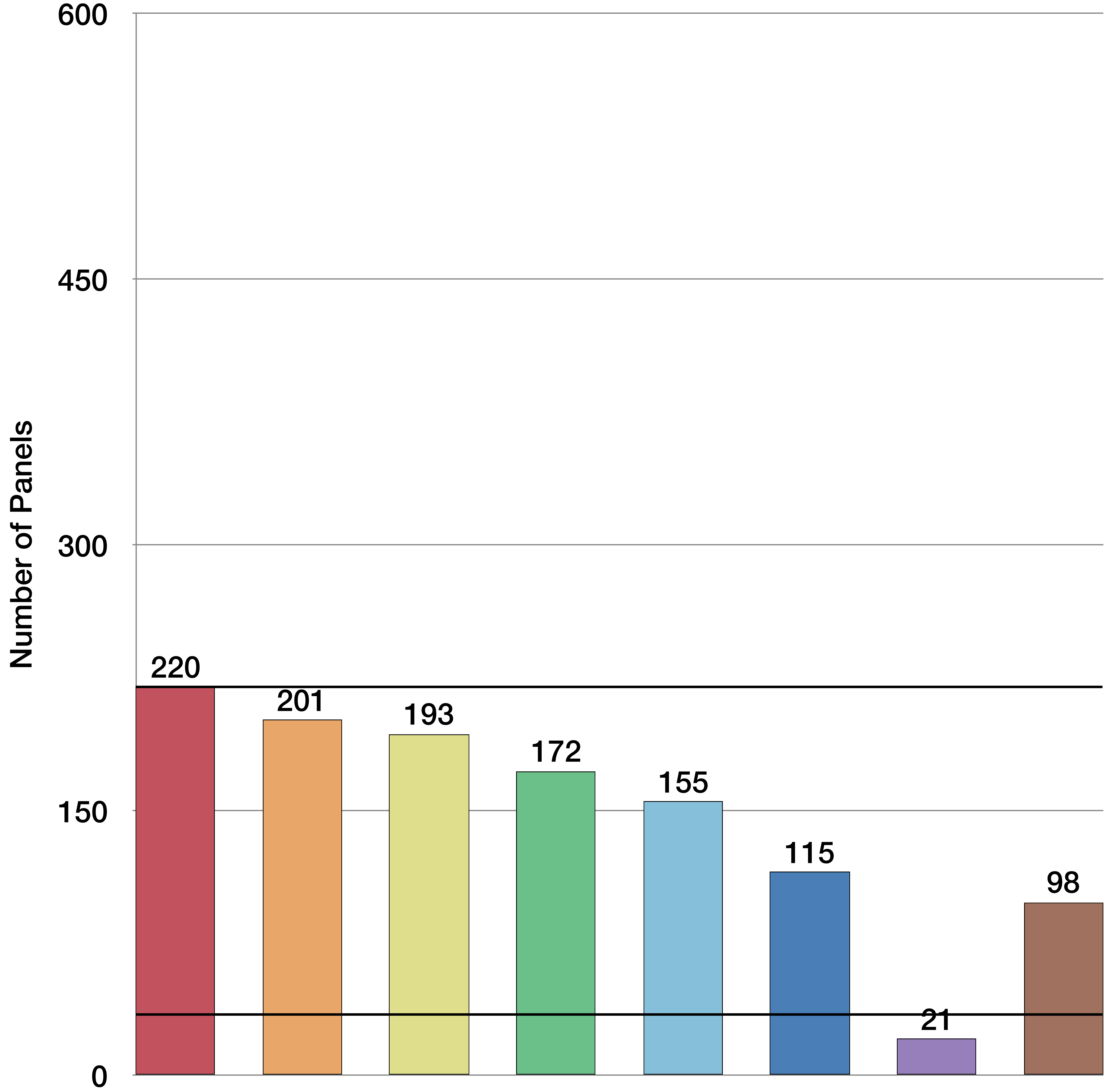
Iterative Reassignment - Iteration 15



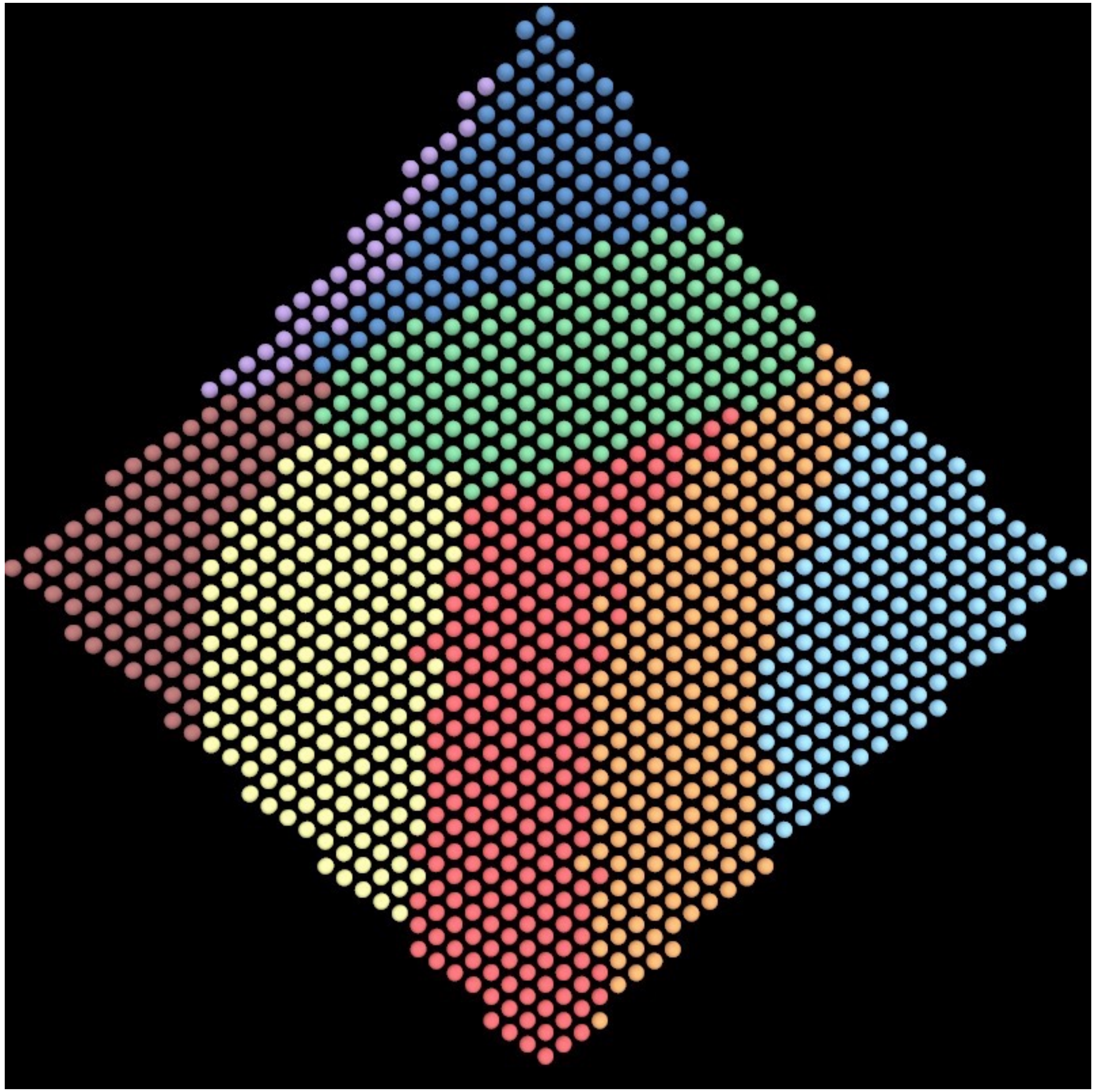


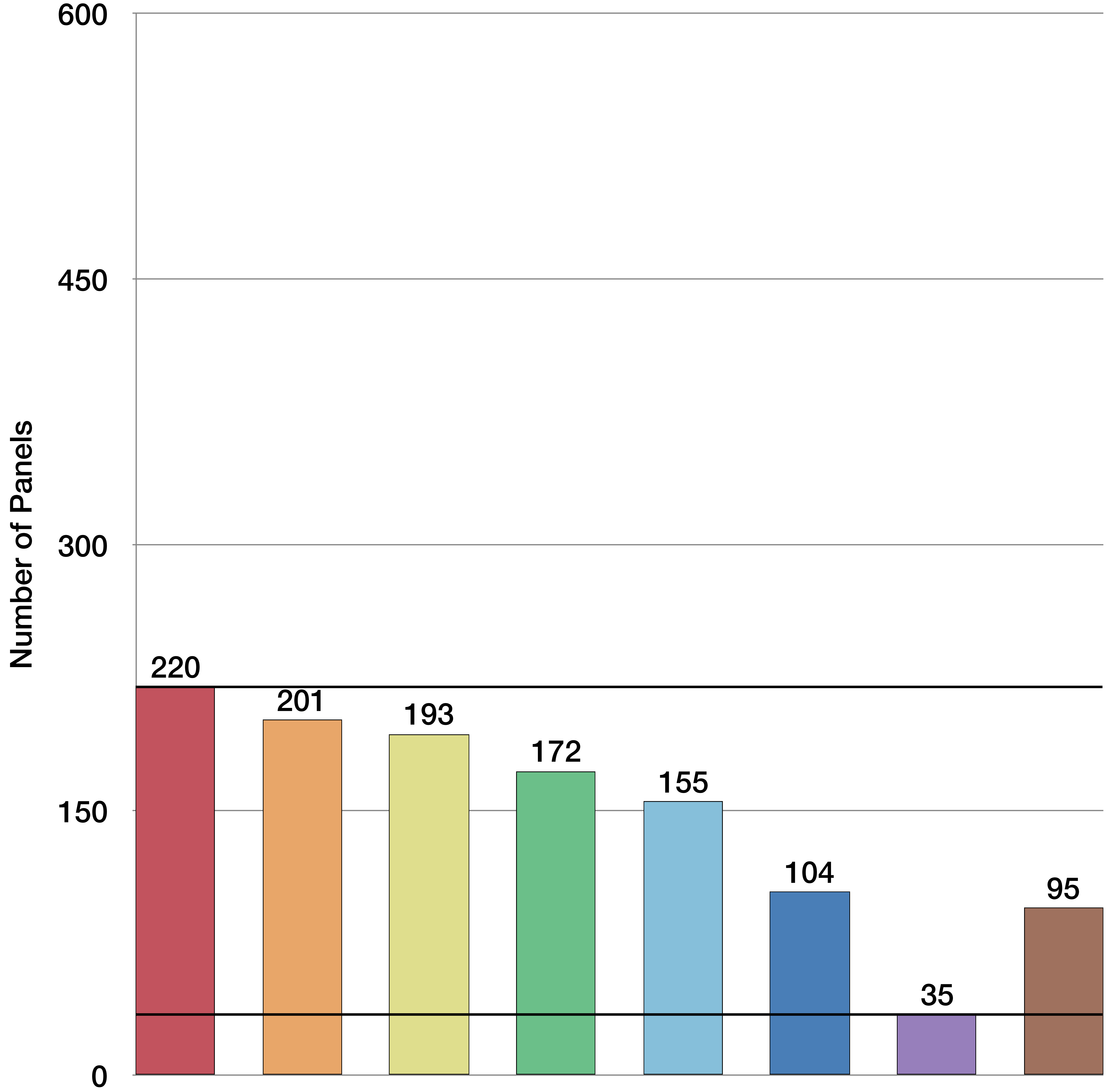
Iterative Reassignment - Iteration 16





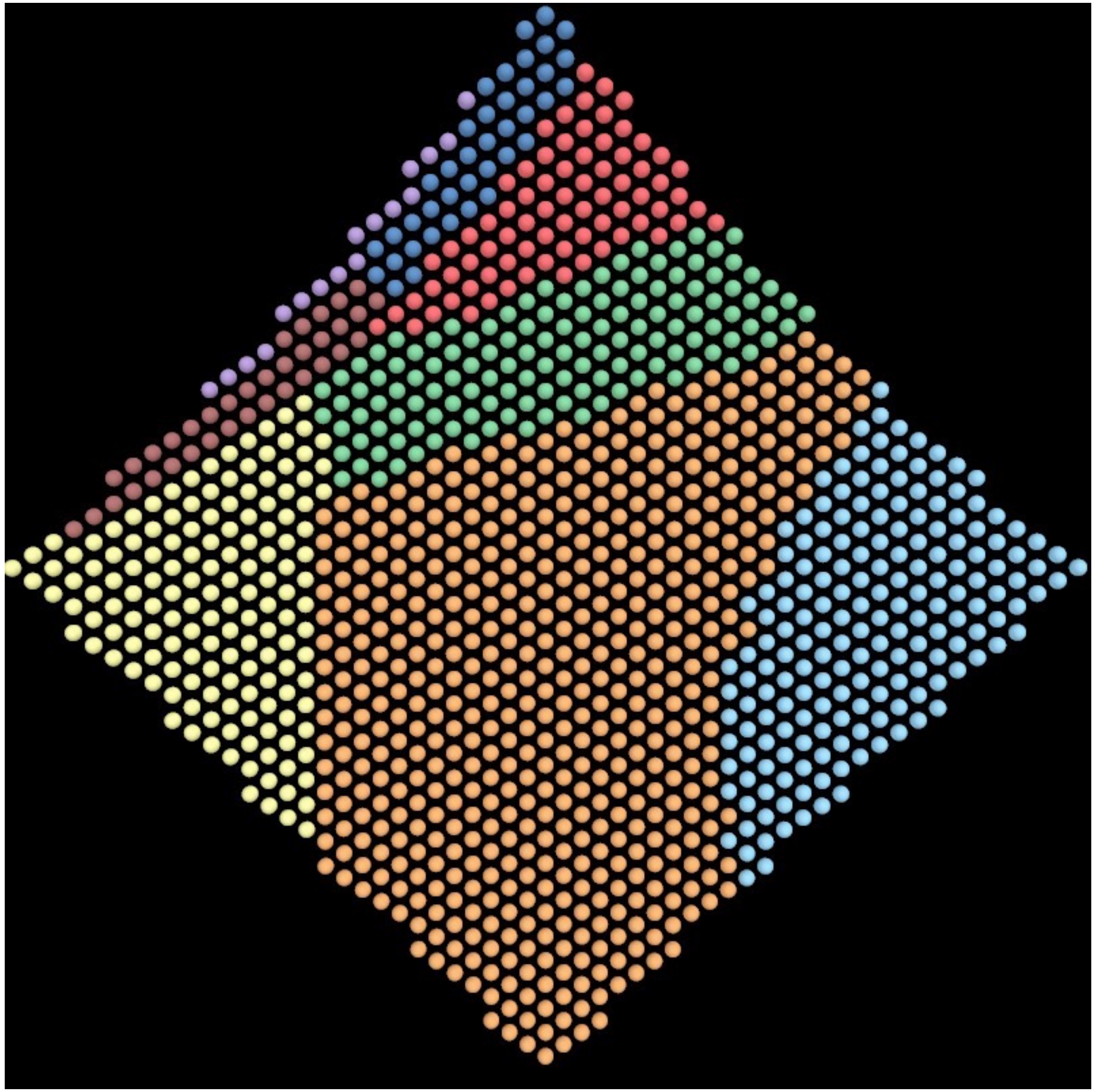
Iterative Reassignment - Iteration 17

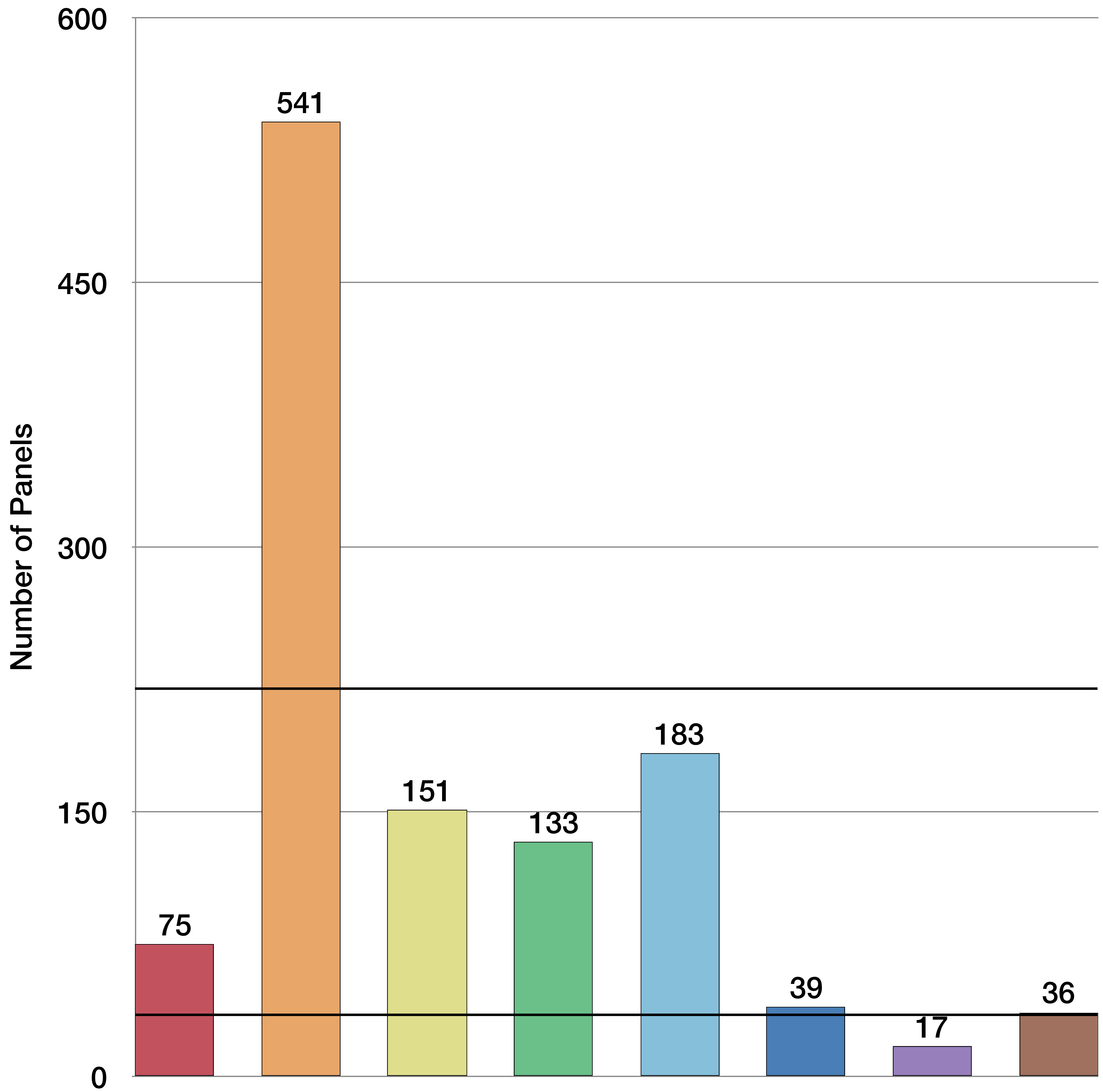




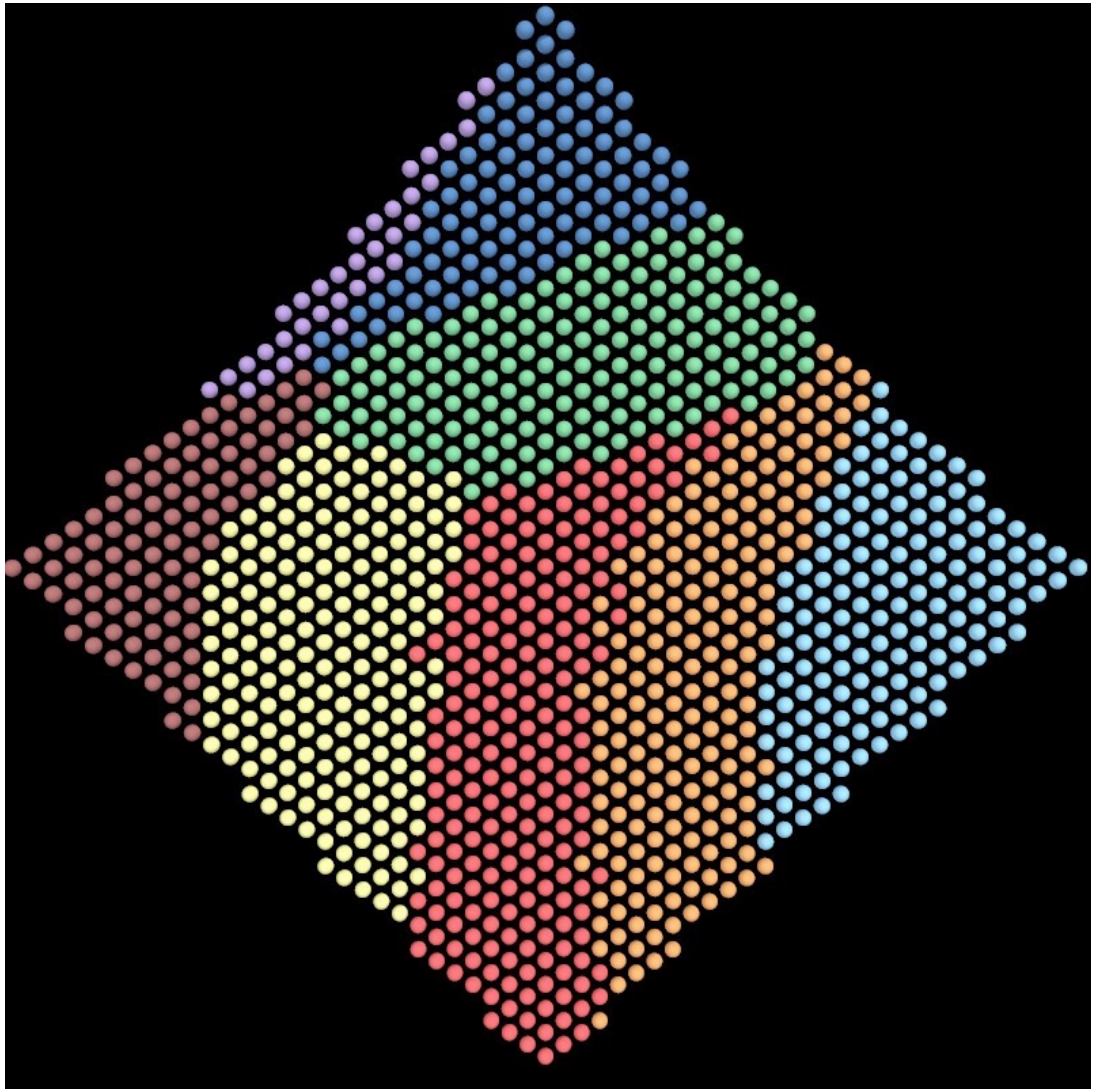
Clustering result and reassignment outcome

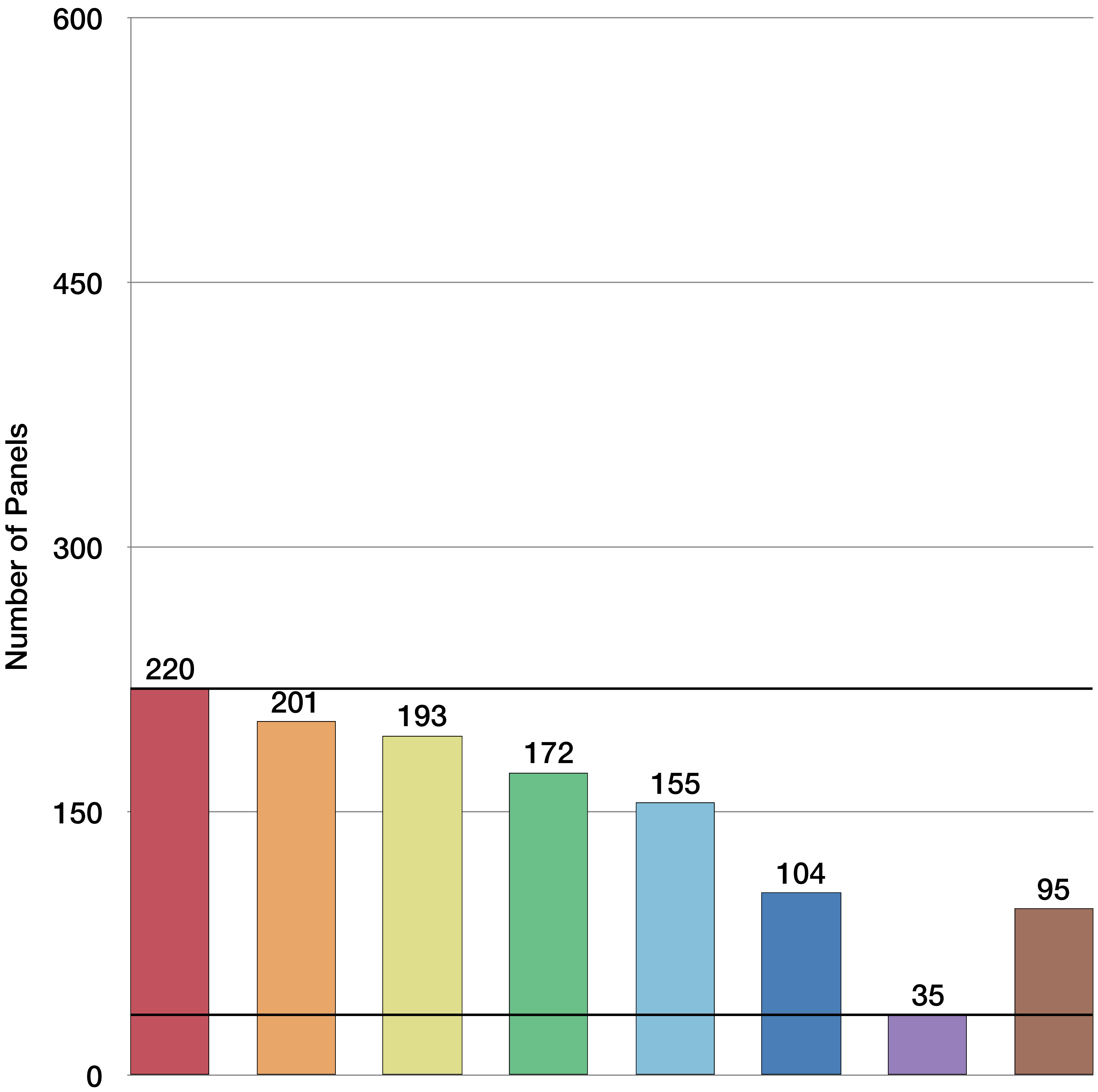
Clustering Result - Bay 05



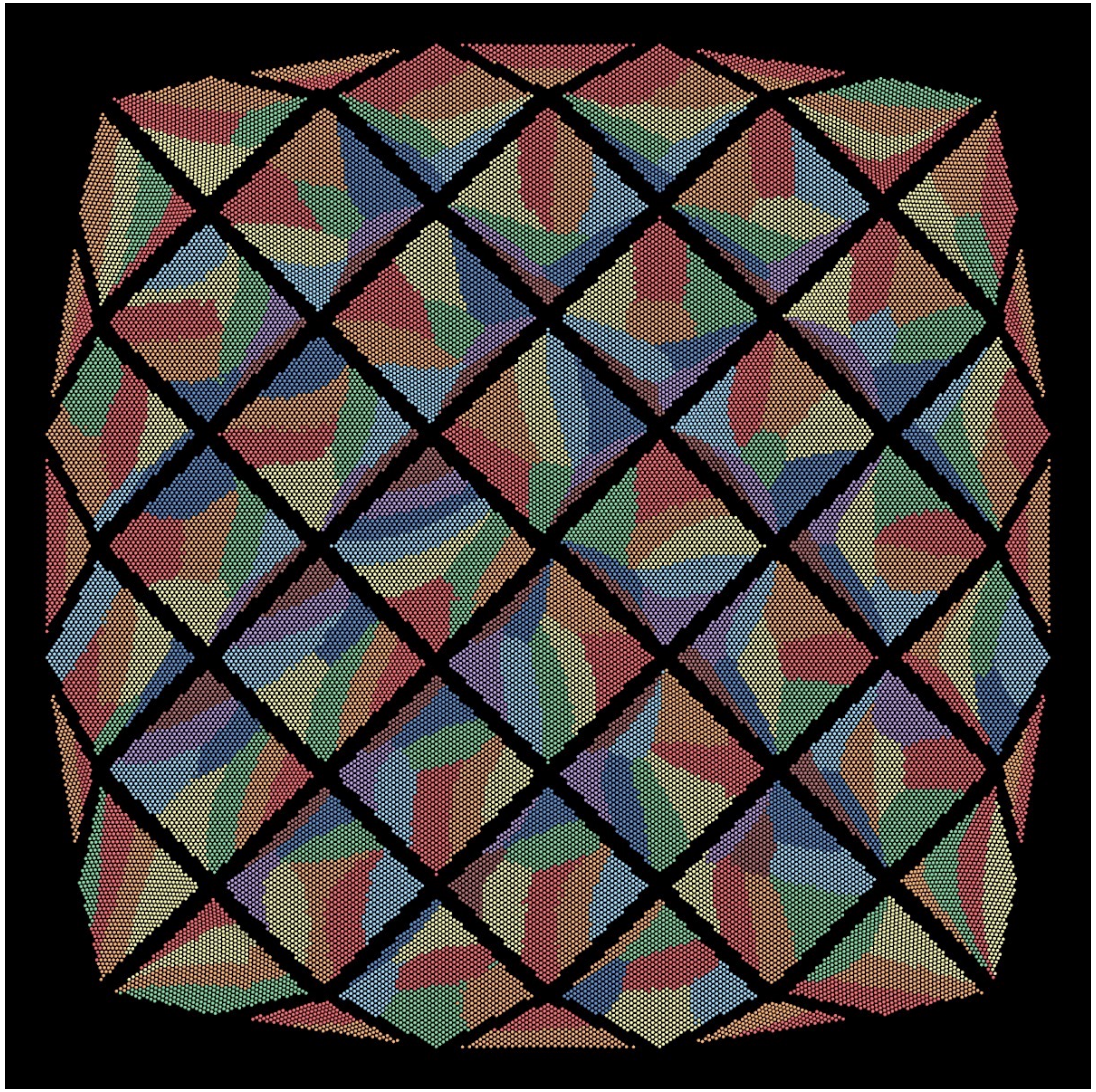


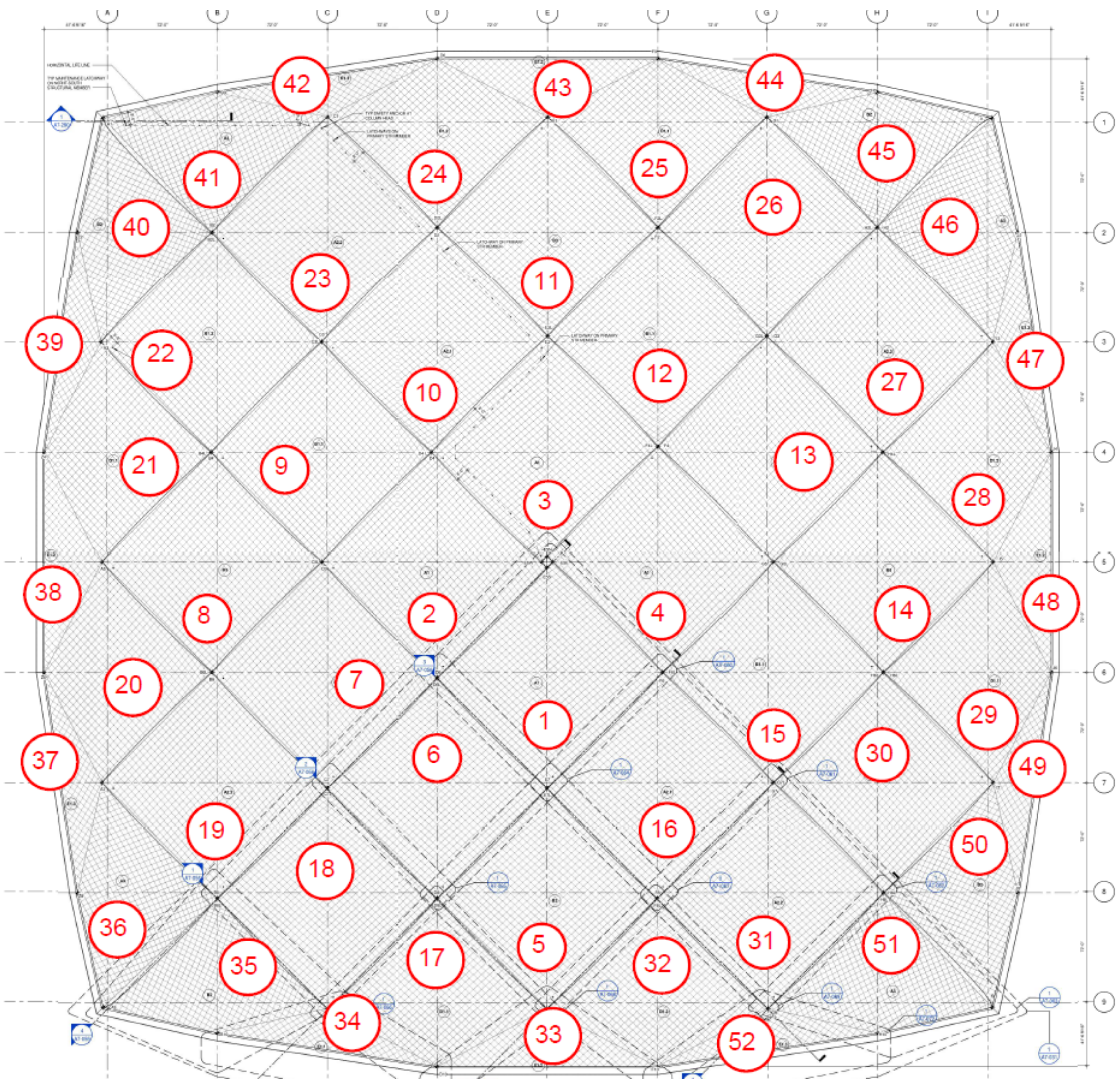
Iterative Reassignment - Iteration 17





PV Zones - All Bays





Step Two

Estimating Hourly Energy Production

Hybrid Radiance - PVWatts Method.

- PVWatts calculation provides an accurate estimate of annual PV energy production because it accounts for the following:
    - Temperature of the panel and effect on panel output
    - Off normal transmission of the PV cover glass
    - Non-linear inverter efficiency
- However the PVWatts calculation is **unable to account for shading** from site context or building self-shading. The shape of the roof creates substantial shading for PV panels near the clearstories.
- We employed a hybrid Radiance-PVWatts calculation method that uses Radiance to calculate shading and PVWatts to calculate panel output.

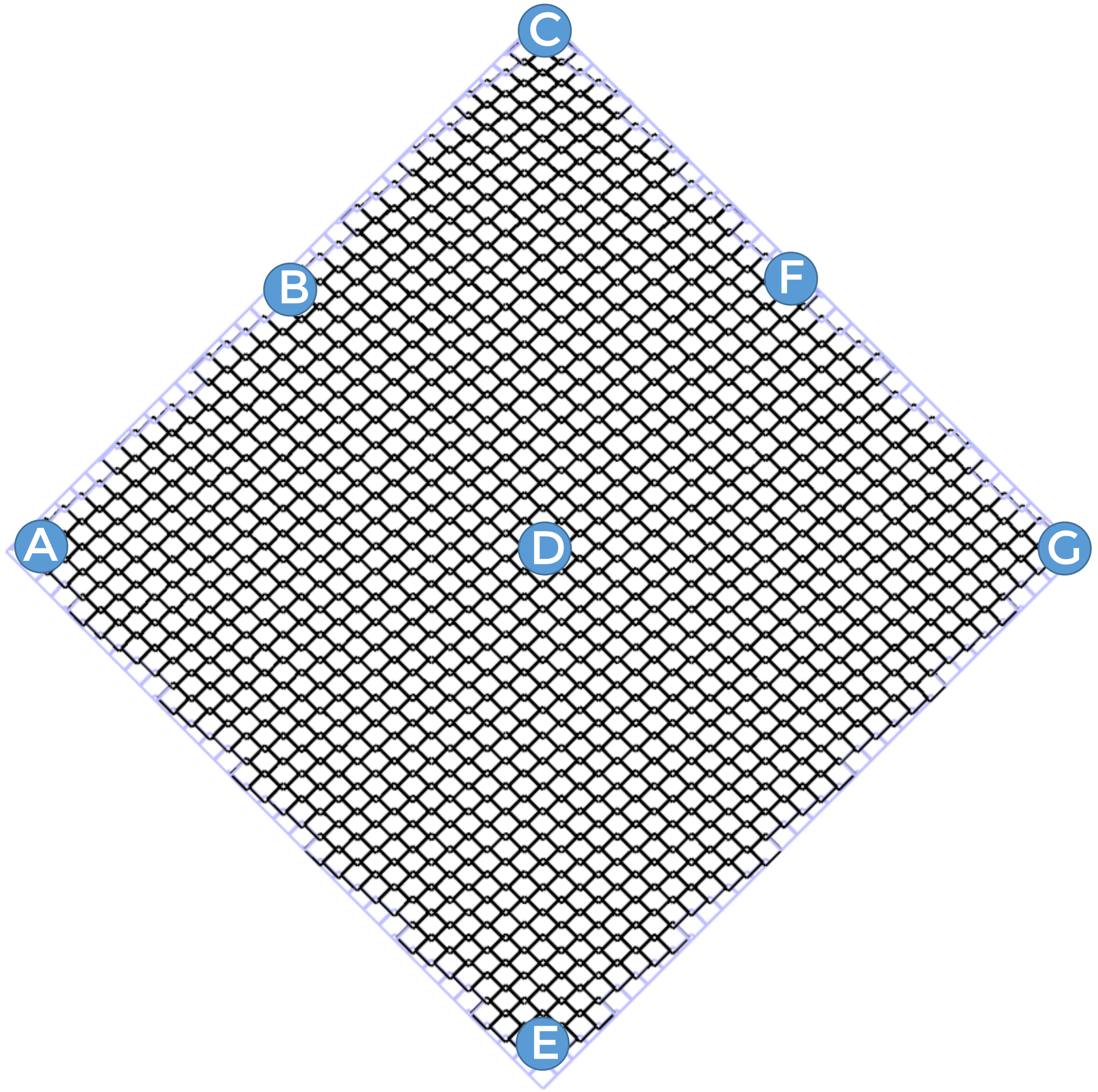
Hybrid Radiance-PVWatts Method.

- Shading correction factor – In Radiance simulate hourly irradiance for each panel in two conditions: unshaded (nothing in the model) and shaded (building roof included in the model). A shading correction factor can then be calculated for each hour of the year by dividing shaded irradiance by unshaded irradiance.

- Calculate the hourly DC power output for each panel with PVWatts

- Multiply the hourly DC power output by the hourly shade factor to account for shading.

Comparing PV-Watts and Radiance Irradiance Calculation



Compare panel irradiance results between PVwatts and Radiance using seven panels from bay 05

	Tilt	Azimuth
A	21	39
B	5	138
C	35	147
D	1	336
E	1	159
F	5	154
G	22	261

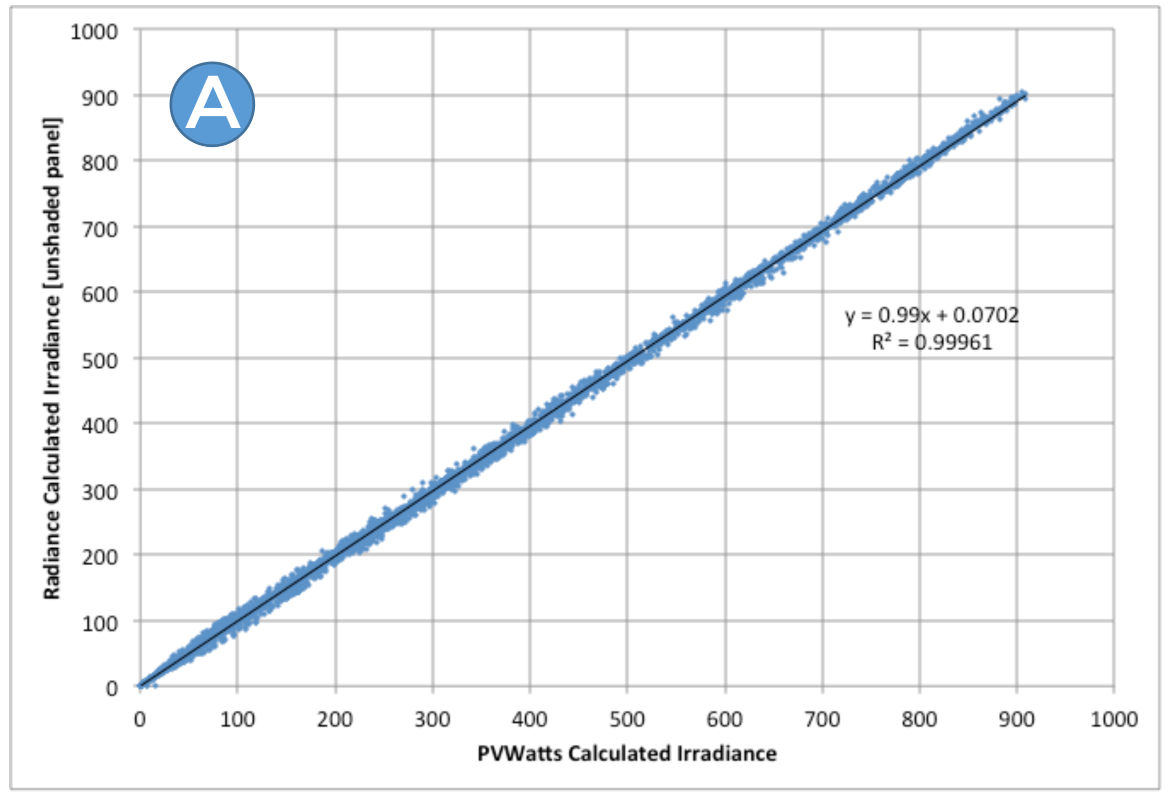
Tilt is measured from horizontal, a vertical panel has a tilt of 90 degrees. Azimuth is measured from North, which is 0 degrees. East is 90 degrees, South is 180 and West is 270. Despite the 183 difference in azimuth angle panel D and E have nearly the same aiming, since they have tilt angles of 1 degree (pointing nearly straight up).

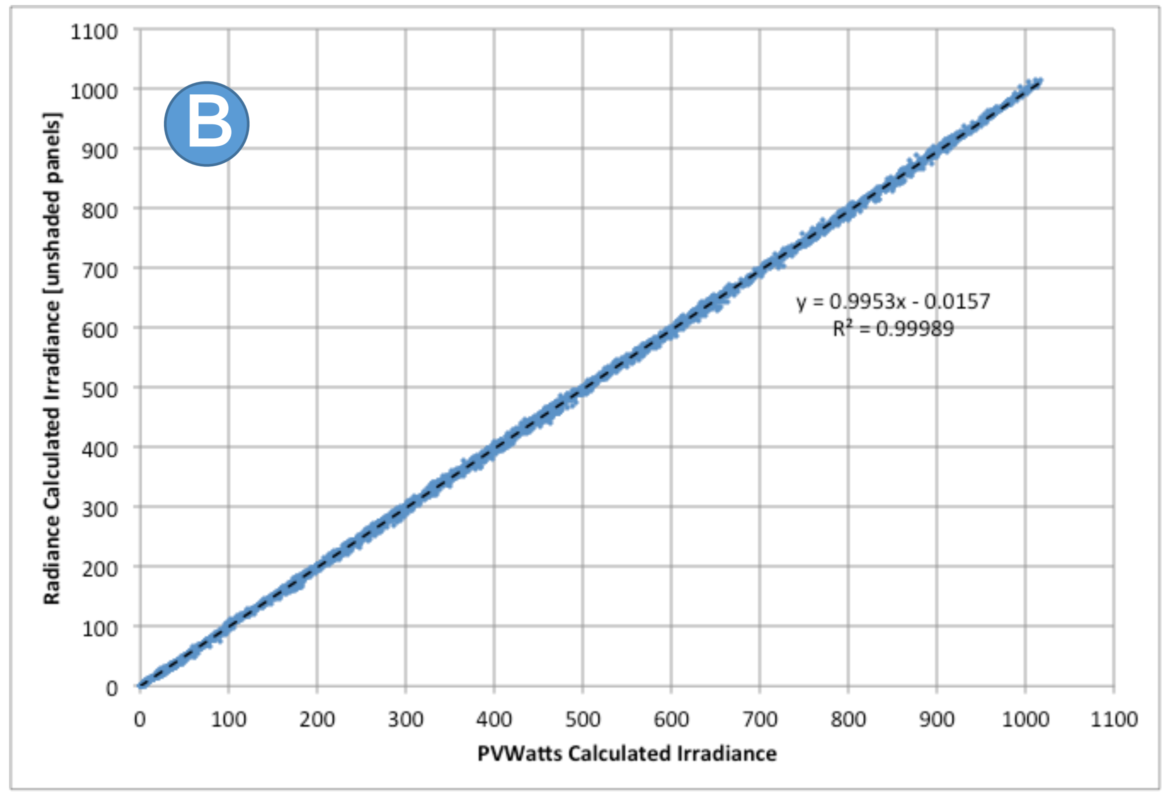
Radiance vs. PV Watts Irradiance Comparisons – Bay05

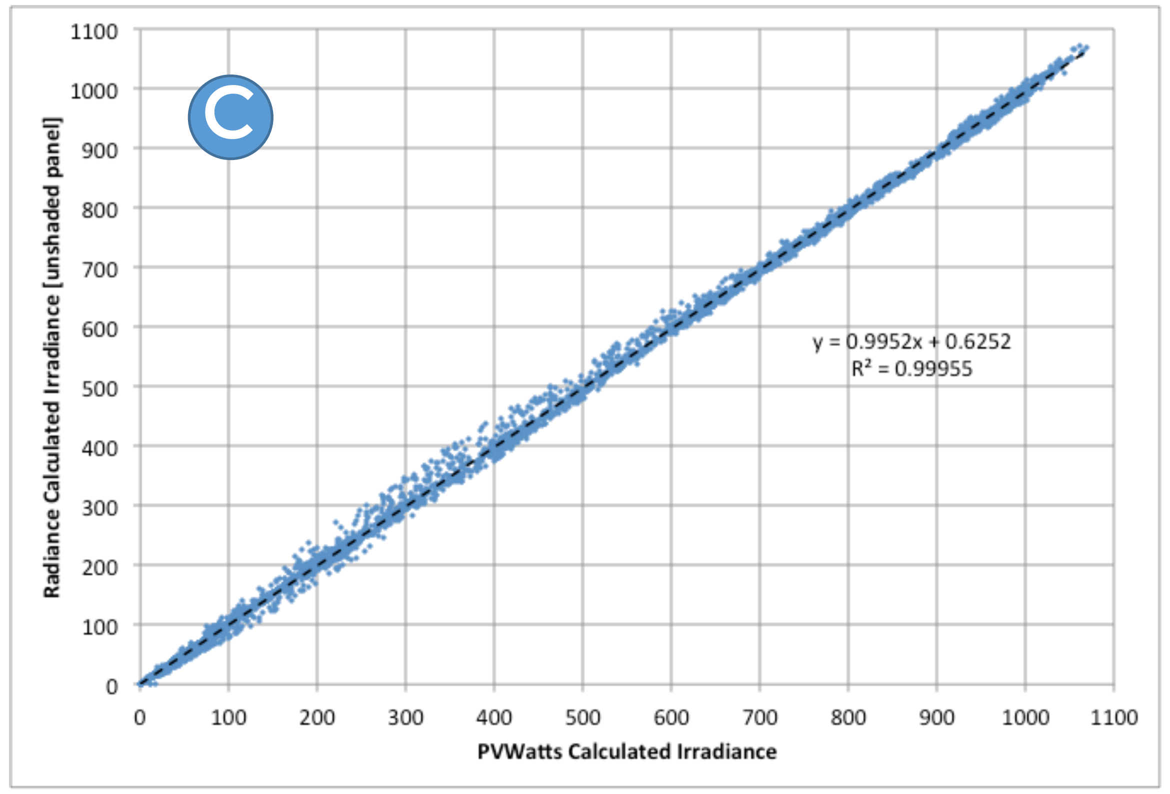
Radiance vs. PVWatts (x-axis) for unshaded panels

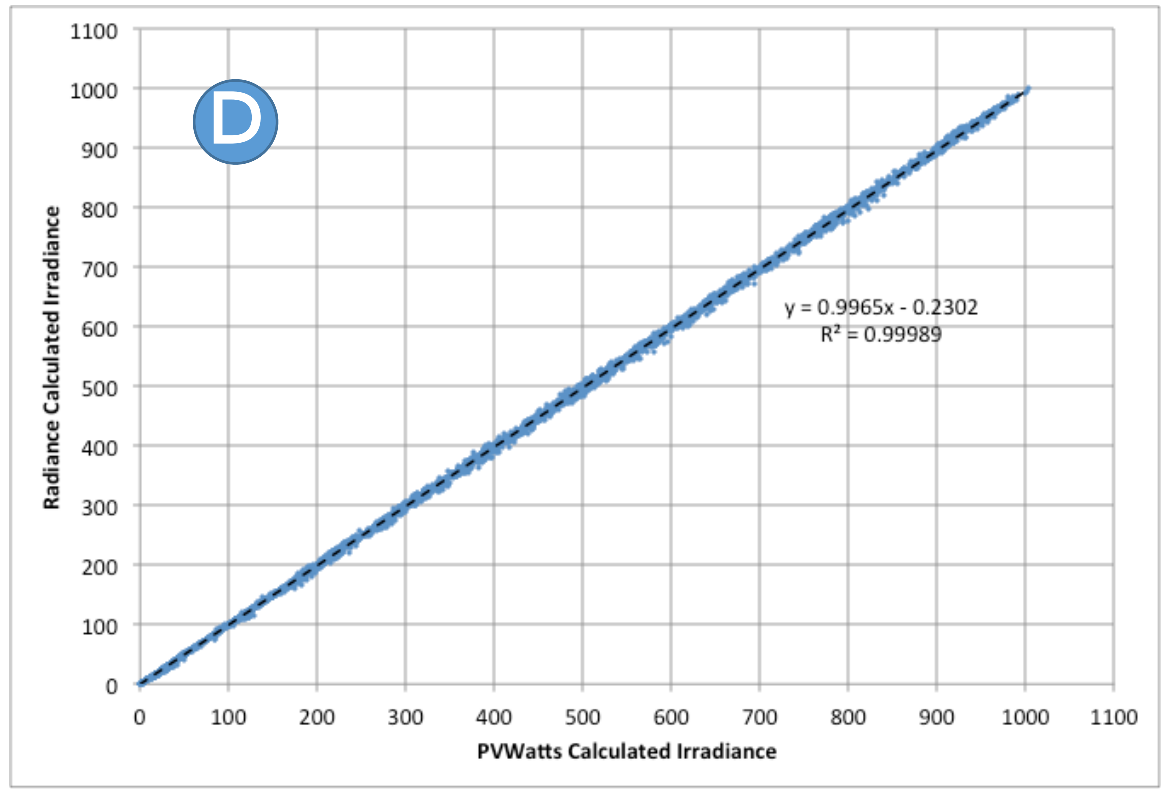
Panels with near zero tilt angle have nearly perfect agreement. As the tilt increases, the agreement gets slightly worse.

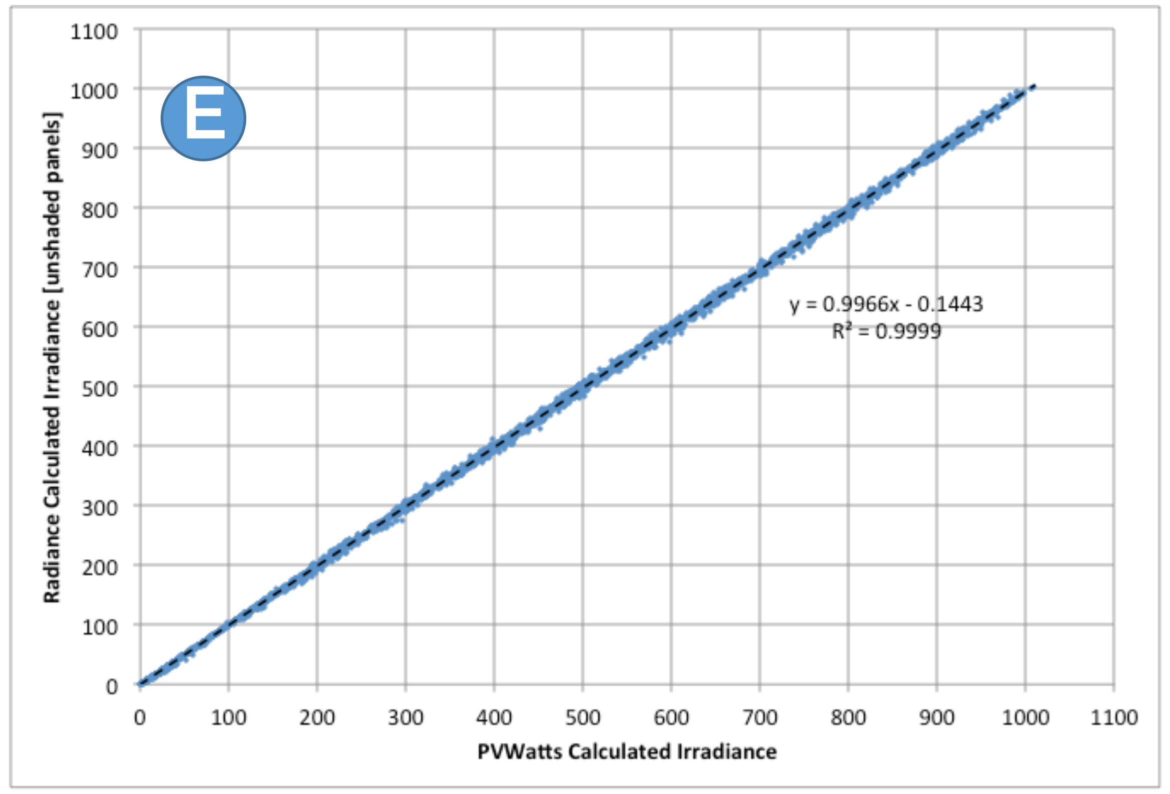
The disagreement between the PVWatts and Radiance likely stems from the difference in sky model used. Radiance uses the Perez All-Weather sky luminance model,[1] while Pvwatts uses Perez's method for modeling irradiance components from direct and global irradiance.[2]

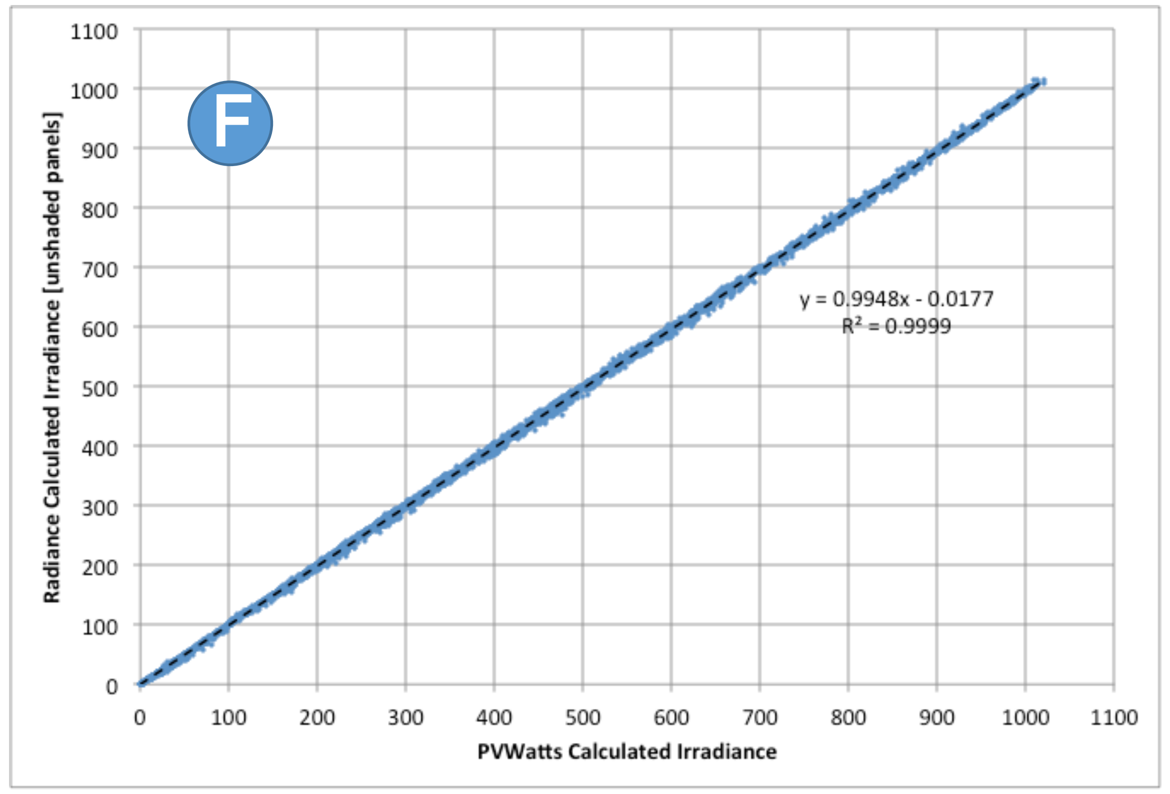


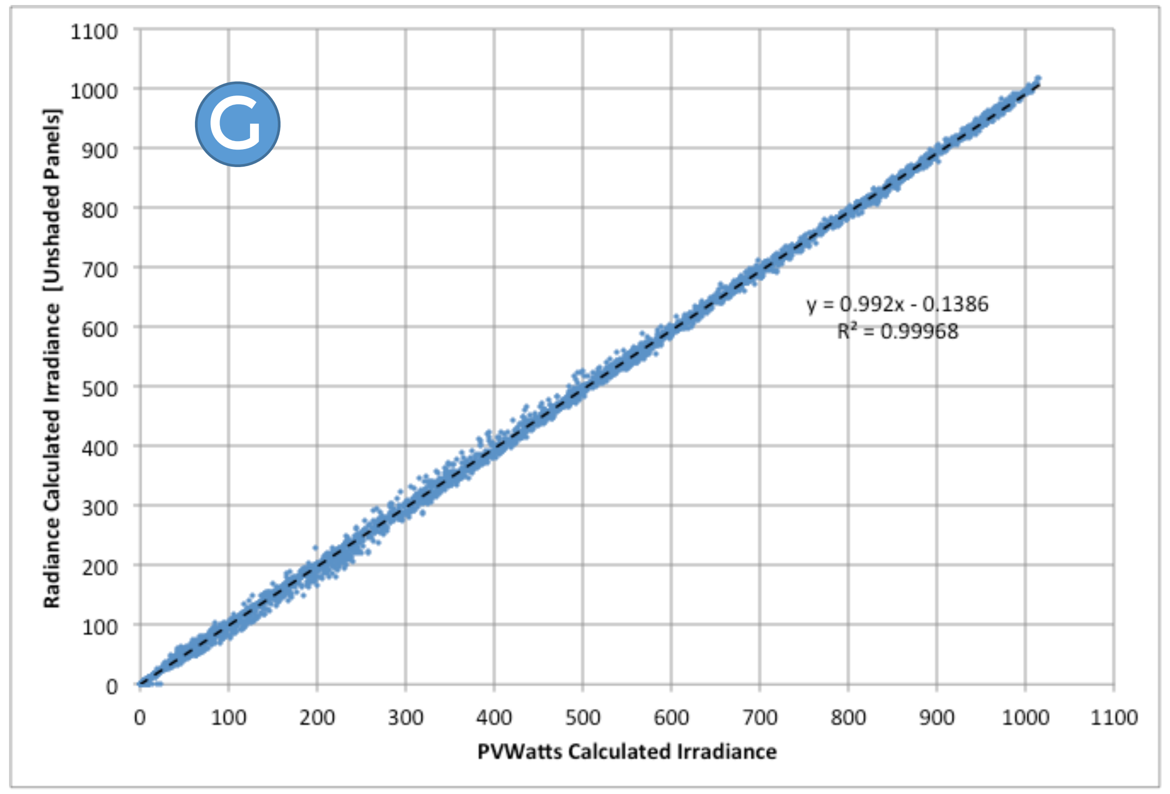












[1] Perez, R., Seals, R. and Michalsky, J., 1993. All-weather model for sky luminance distribution—preliminary configuration and validation. Solar energy, 50(3), pp.235-245.

[2] Perez, R., Ineichen, P., Seals, R., Michalsky, J. and Stewart, R., 1990. Modeling daylight availability and irradiance components from direct and global irradiance. Solar energy, 44(5), pp.271-289.

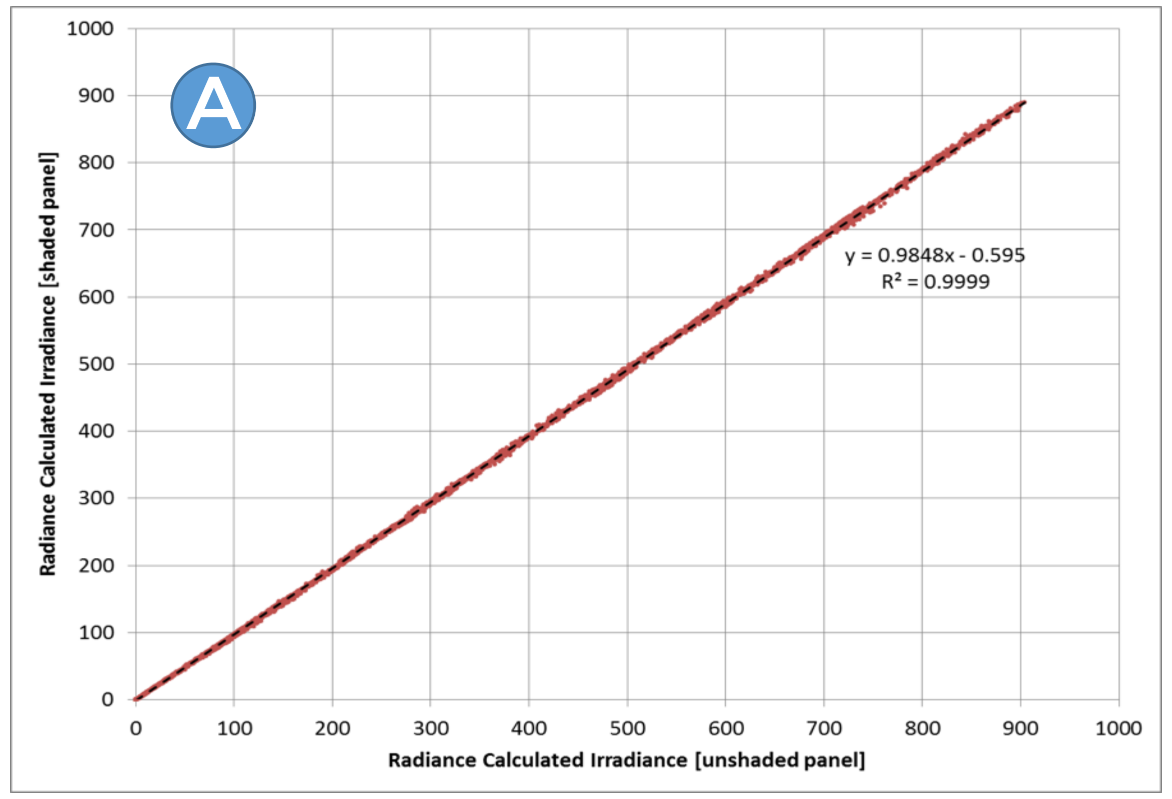
Radiance vs. PV Watts Irradiance Comparisons – Bay05

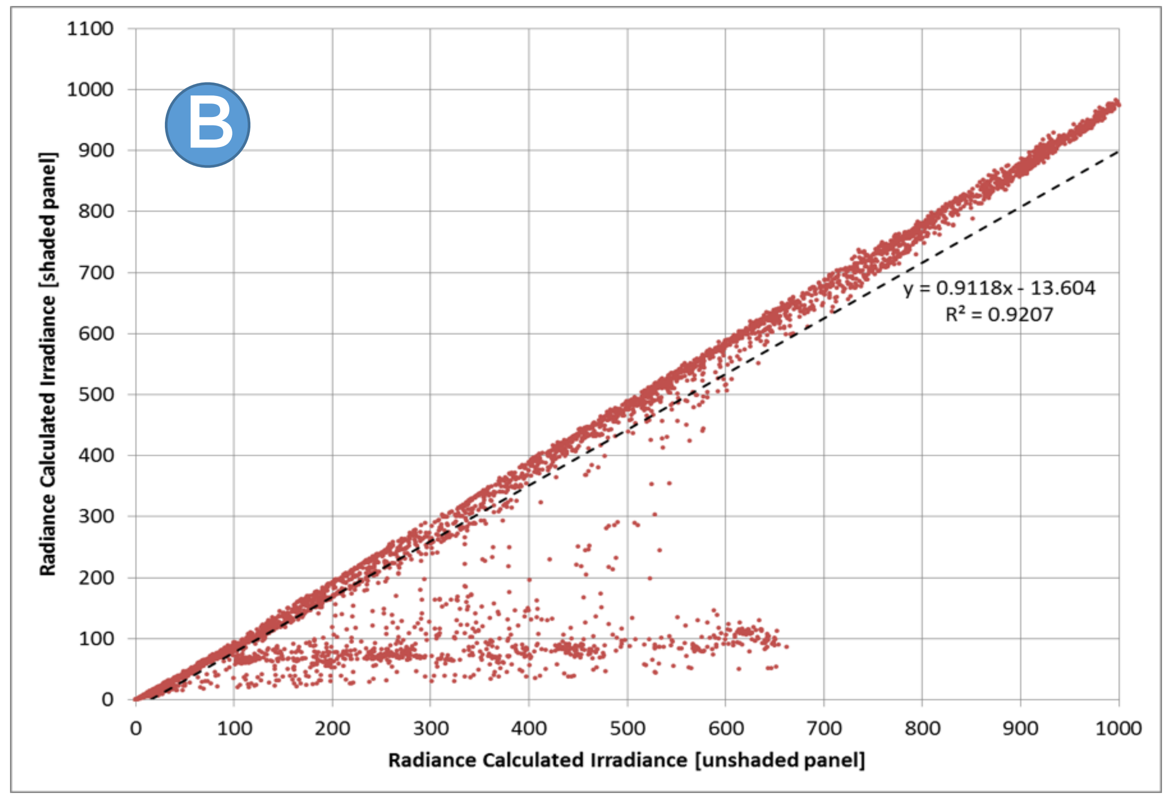
Radiance with shelf shading (y-axis) vs. irradiance without roof self shading (x-axis).

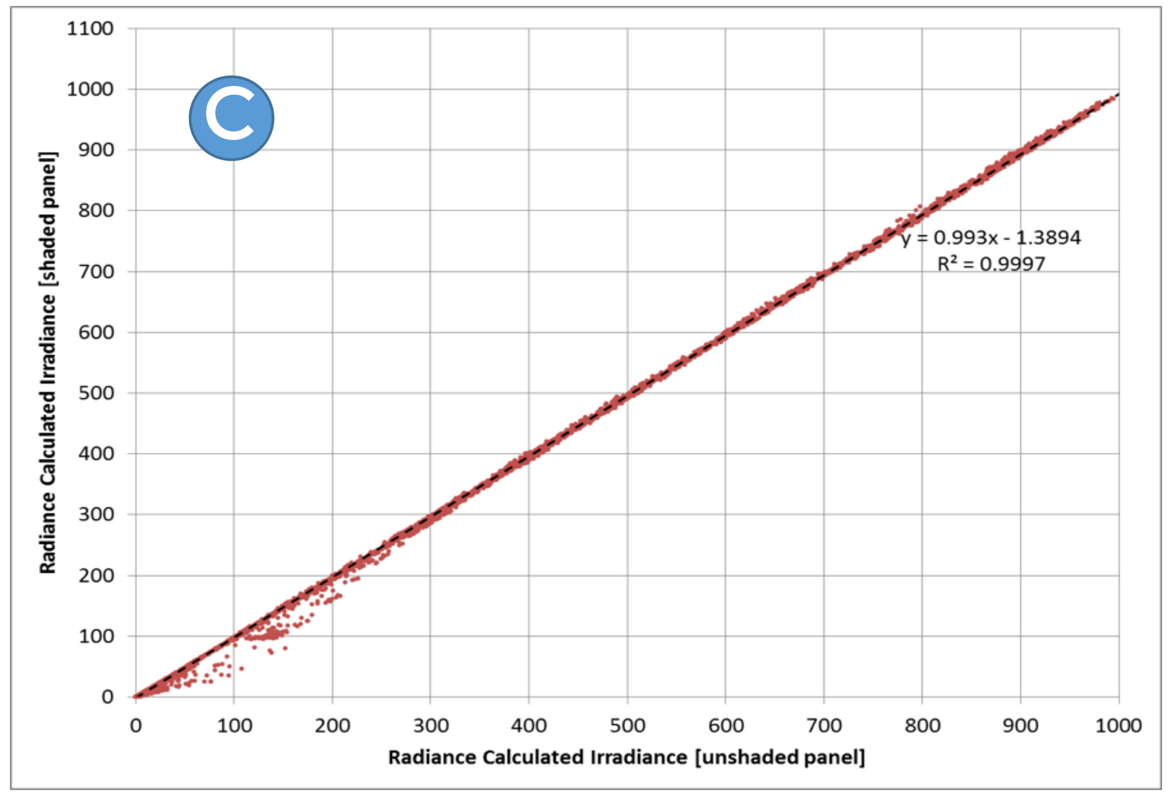
Shading occurs at times where the points fall below the y=x diagonal.

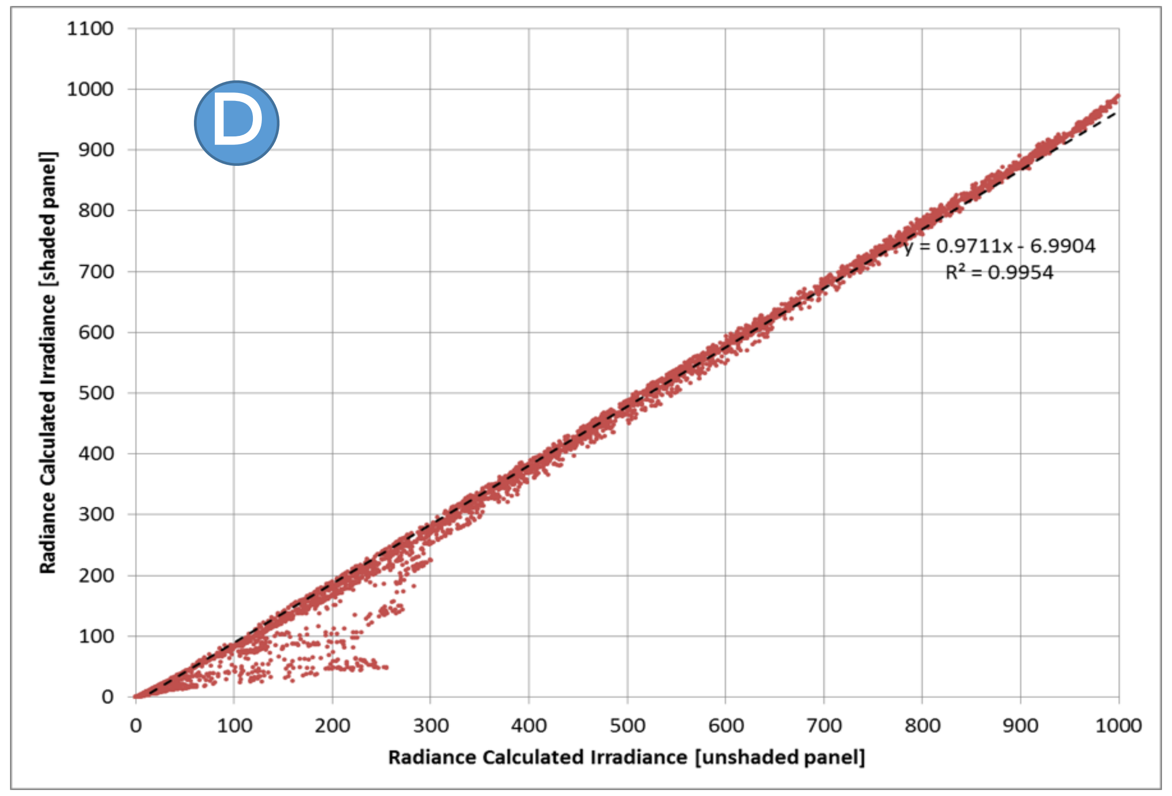
Panel B experience the most shading from the roof, while panel E and A experience almost no shading.

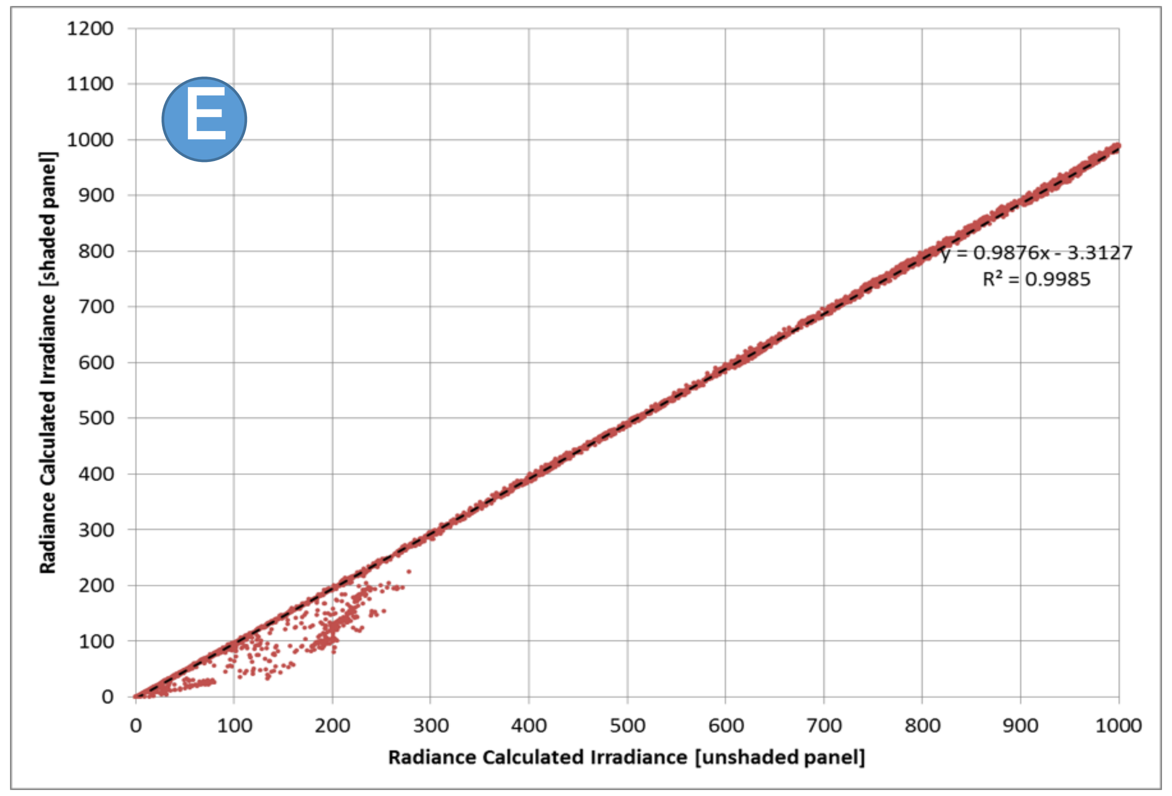
For each hour the ratio of shaded to unshaded irradiance is used to adjust the panel output generated by PVWatts. To account for shade on the panels from the roof.

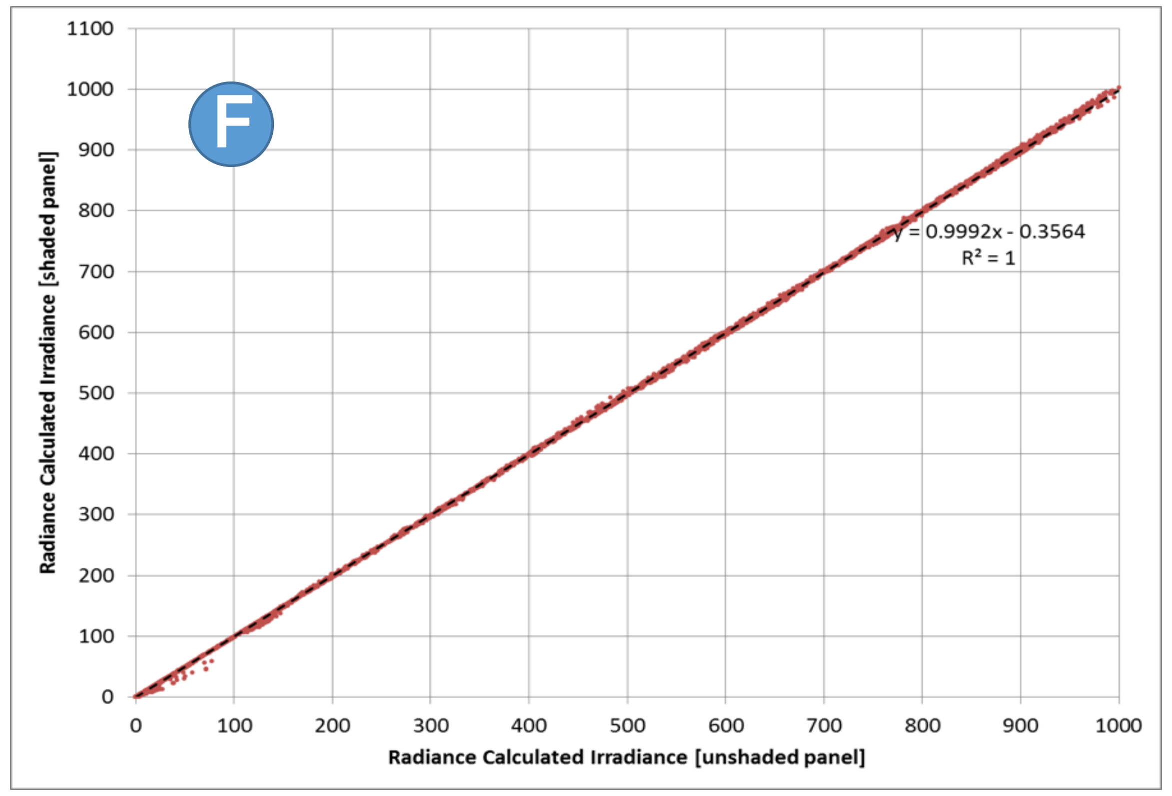


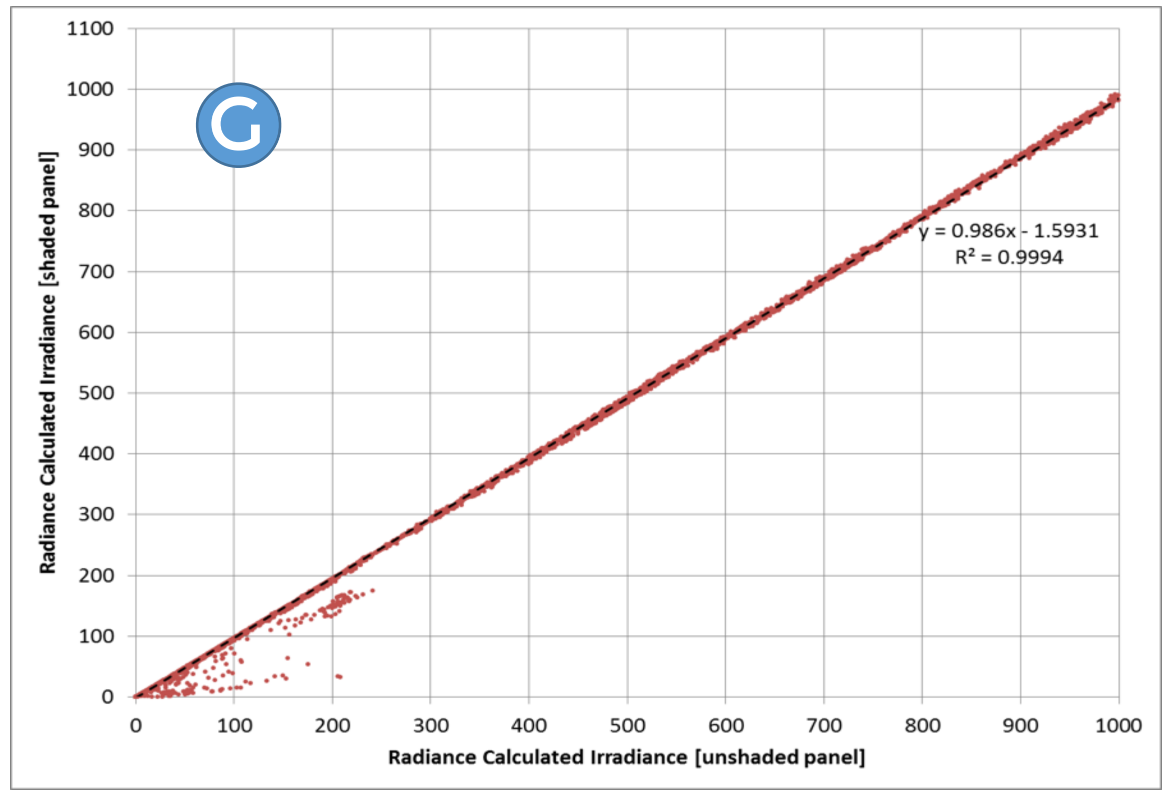












Applying Shade Factor

- Obtain hourly annual DC output of a panel using DC watts API
    - Put these in a radiance matrix file (rows = each panel, cols = hour of the year)
- Generate Shaded daylight coefficient matrix (rfluxmtx)
- Generate Unshaded daylight coefficient matrix (rfluxmtx)
- Multiply Daylight Coefficients by Sky Matrix (rmtxop)
- Multiply DC matrix by shaded irradiance matrix and divide by unshaded irradiance matrix (element wise)

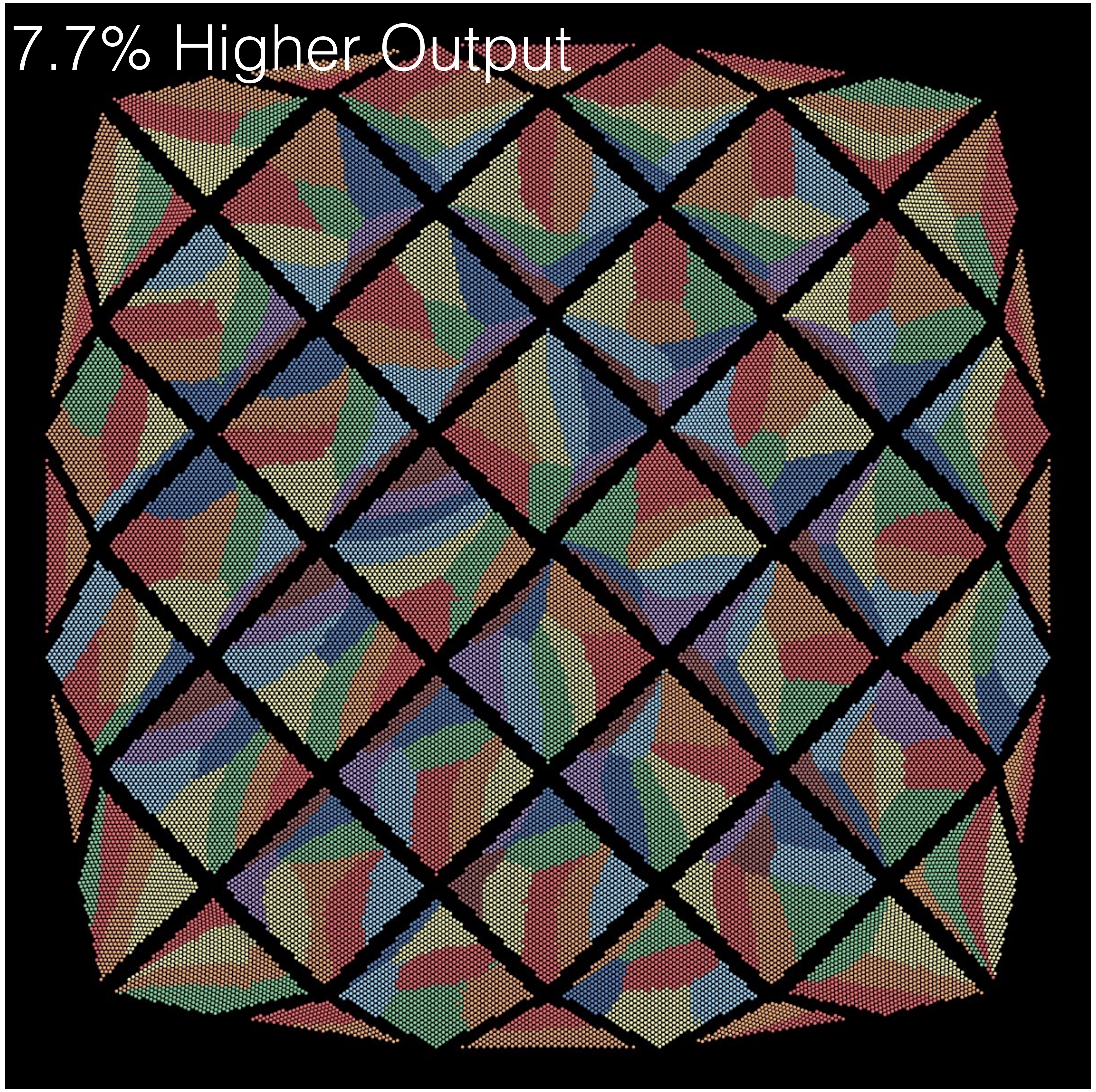
```
rlam -if1 '!rcollate -oc 1 irrad/bay_05-1_unshaded.out | getinfo -' \
          '!rcollate -oc 1 irrad/bay_05-1_shaded.out | getinfo - ' \
          '!rmtxop -ff1 dc_output/bay_05-1.mtx | rcollate -oc 1 | getinfo -' | \
    rcalc -if3 -of1 -e '$1=if($1,$3*$2/$1,0)' | \
    rcollate -hi -ff1 -ic 1 -ir $((numpanels*8760)) -oc 8760 | \
    rmtxop -t -ff - > adjusted_dc/bay_05-1.mtx
```

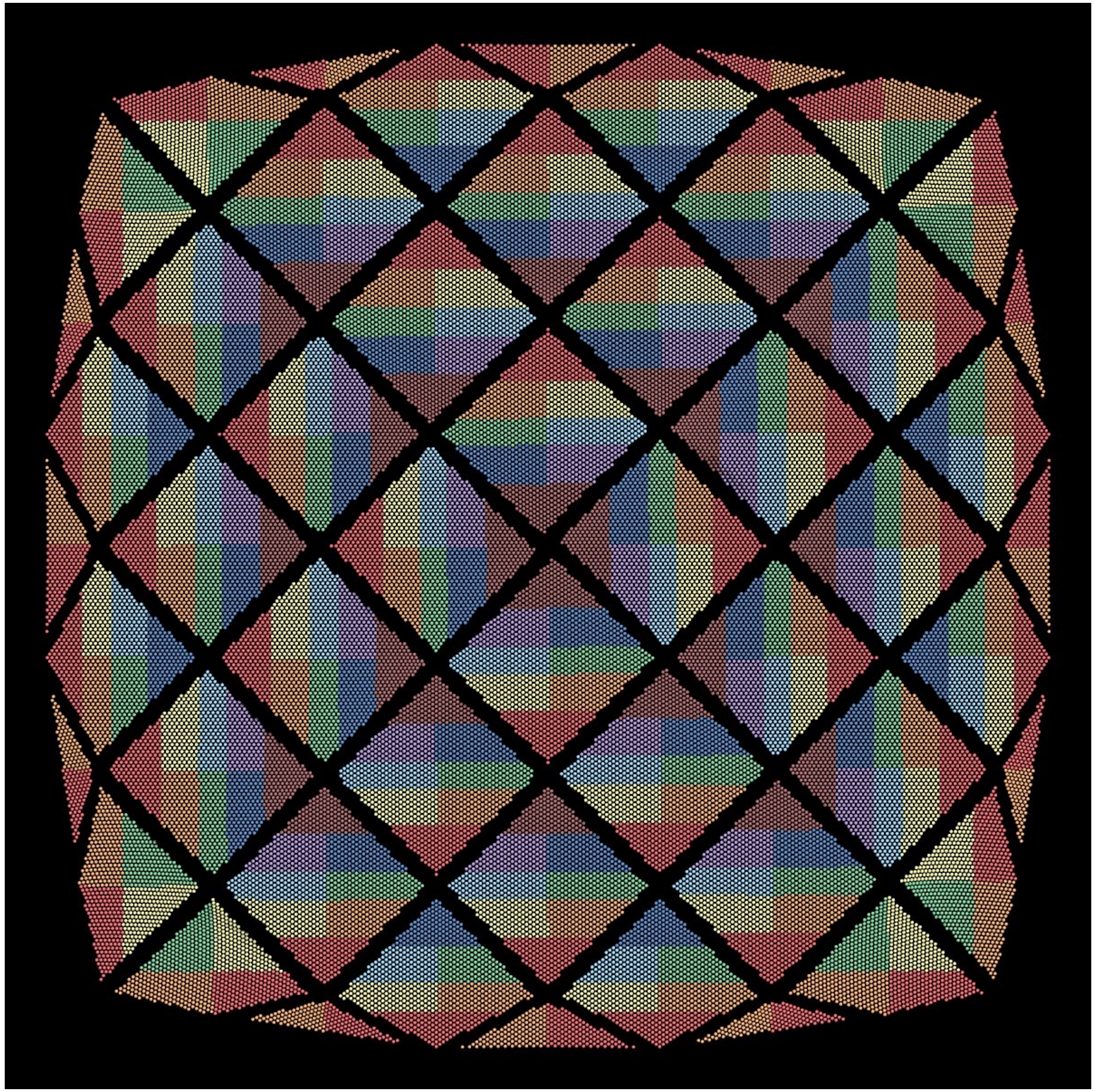
Old way before element wise multiplication and division in rmtxop. Thanks Greg!

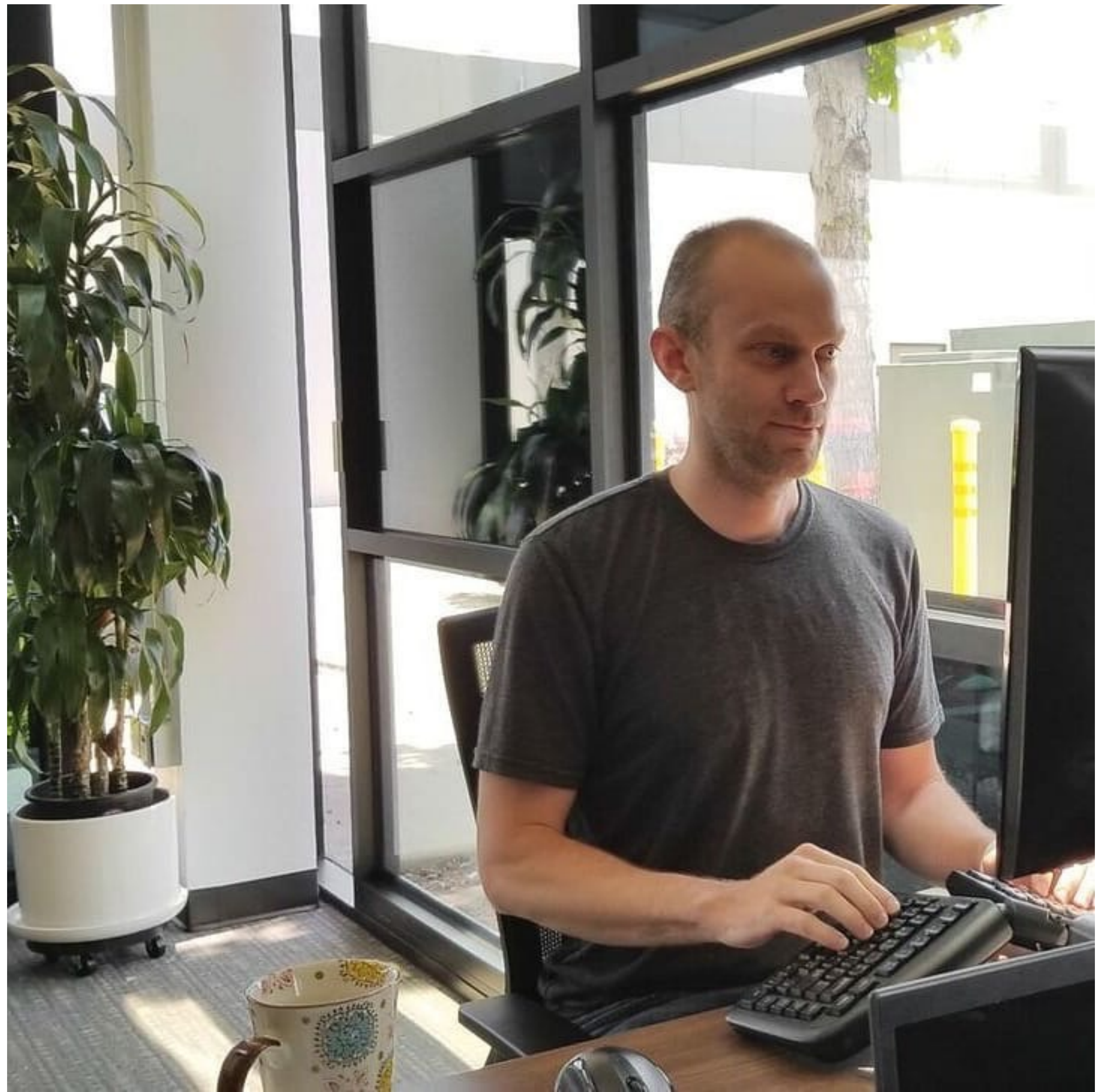
Hybrid Radiance-PVWatts Method.

- Reduce power for all panels in a zone to that of the minimum panel in the zone.
- Cap power output at 15 kW for zones exceeding maximum output.
- Apply inverter efficiency and sum all zones and bays.

Clustered Panels vs. Simple Grid Grouping







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