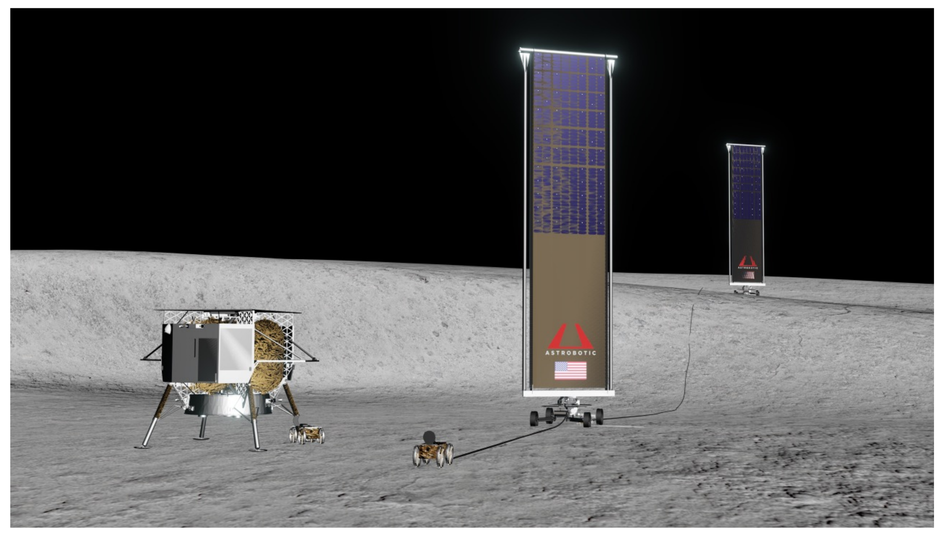

Credit: Andrew Grove

Design Optimization of Megawatt Scale Lunar VSAT Arrays

The Vertical Solar Array Technology, or VSAT, is a strong candidate for modest powered missions to the Lunar Poles (1). It features an elevated, vertically oriented panel which rotates to always face the Sun. For sites very near the poles, the Sun remains very close to the horizon, which allows a rotating vertical panel to continually receive almost normal-incidence sunlight, therefore maximizing its insolation. However, if multiple VSATs are combined to form an array, this same feature causes a maximal shade behind each panel, potentially decreasing the insolation of the other ones. As the full grid approaches megawatt power generation, placement of the VSATs to Two novel ideas are developed and applied to the 'Connecting Ridge' site near the Lunar South Pole. They are (1) use of a binary bitmask to greatly speed the illumination computation, and (2) optimizing the 'value' of the energy rather than total energy.

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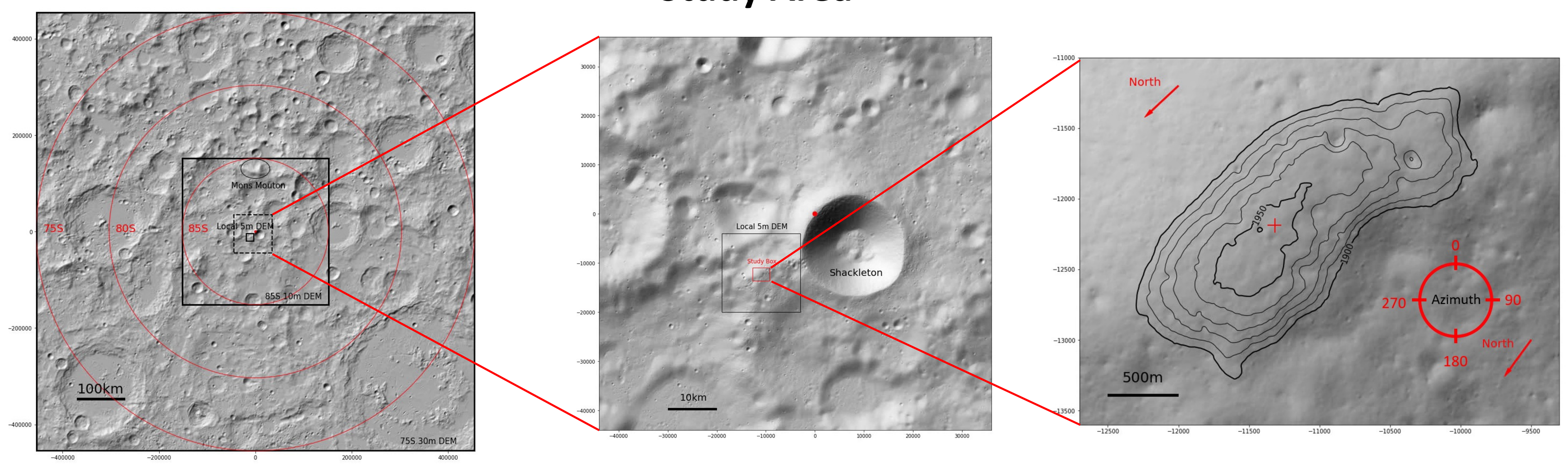
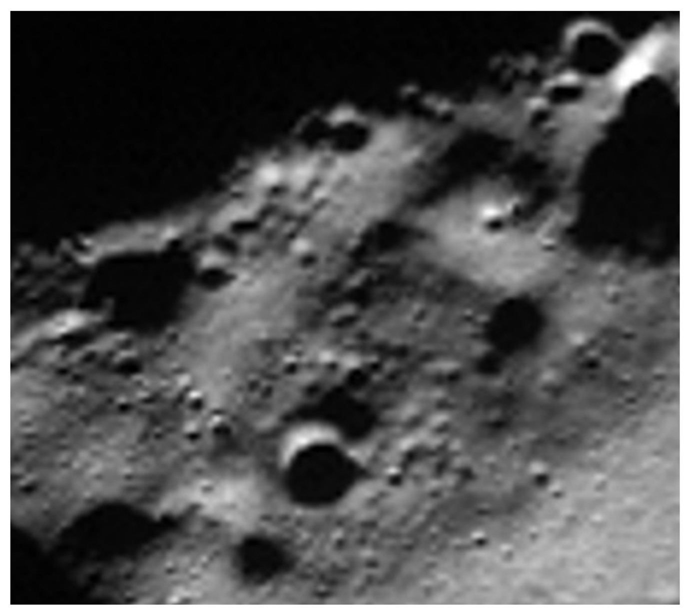
Yann Freudenreich: Yann Freudenreich is a geophysicist currently working as Subsurface Analytics Manager at Shell. He has held a broad range of roles in technology strategy and deployment, geophysical operations, corporate relations, and software development. He holds a PhD degree in Geophysics from Cambridge University (UK) and a degree in Physics from Pau University (FR).

Study Area

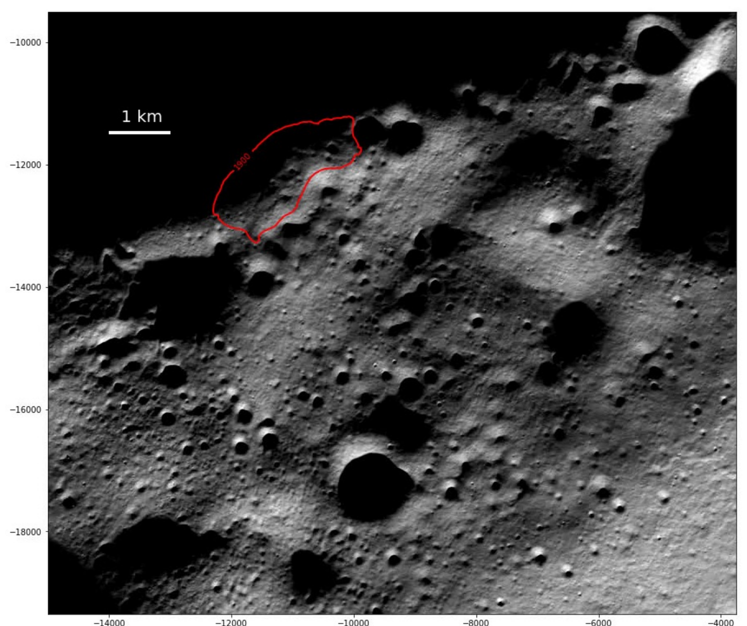


Context of the study area. The South Pole is indicated by a small red dot at (0,0), on the rim of Shackleton Crater. This area is often called the "Connecting Ridge" and is a strong candidate for a landing site with high activity and large power demand. The small red cross marks the VSAT location used for the horizon bitmask illustration.

Illumination Algorithm verification



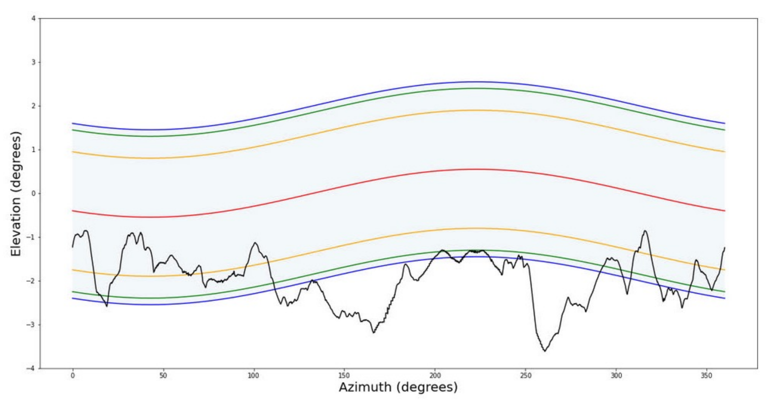
Crop of frame M146392467M of the LRO Wide-angle camera, taken on Dec. 7, 2010 at 20:19:59 UTC.



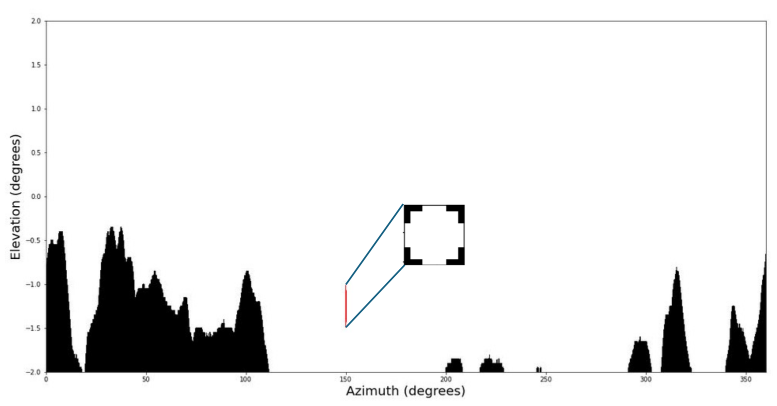
Modeled insolation of the same location at the same time as the LRO photo. The Connecting Ridge site is the red contour.

Bitmask Illumination method

Reducing the illumination computation to an 'AND' operation



A 360° elevation plot of the local horizon as seen from the VSAT sample location. The central red curve indicates the notional path the Sun would take if it were at a constant horizontal (0°) elevation as seen from the pole, i.e., at an equinox. The next set outward (orange) indicates the center of the Sun in extreme summer and winter, i.e., at a solstice. The next set (green) adds the Sun radius of 0.25 degrees. The path of the Sun will vary slightly at different nearby locations in the study area, so the outermost set (blue) is at +/- 2 degrees from the central curve to ensure that no part of the Sun is ever outside the corridor as viewed from any of these vantage points.



Mapping of the shaded swath between the outer lines in Fig. 5a to a rectangular bitmask where each pixel represents a 0.05-degree square. A sample sun position is shown in red, which emphasizes the extreme vertical stretch of the image. The actual sun 10x10 bitmap with no stretching is shown in the inset.

Algorithm pseudo-code for panel array growth

Define:

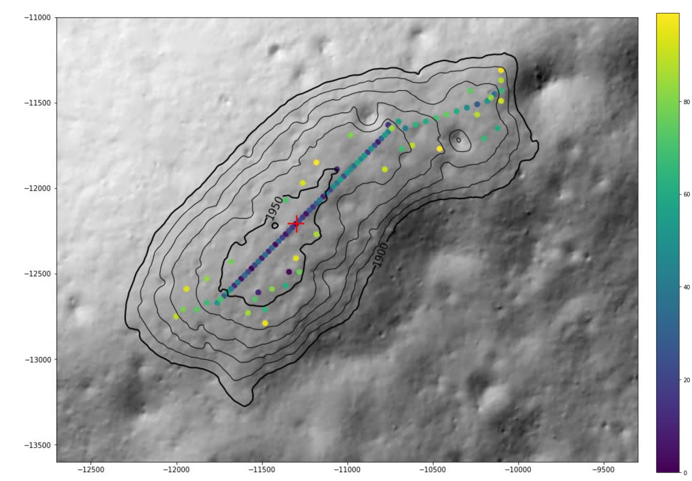
- P as the set of permanently selected panels
- C as the set of remaining candidate panels
- S(A) as the summed energy $E = \sum_t insolation(t)$ for panel set A during the time period

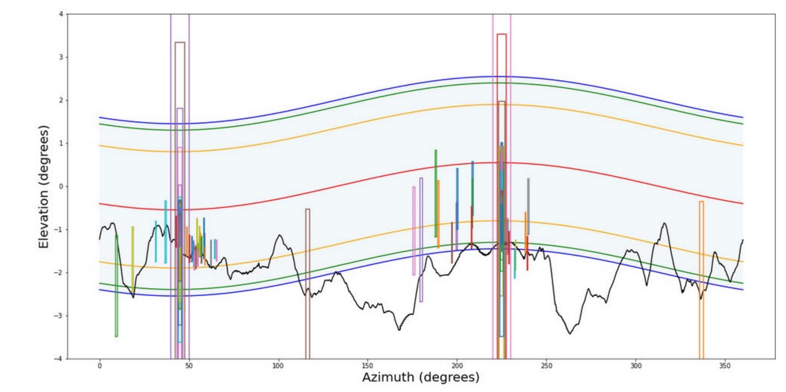
Then, a pseudo-code algorithm would choose the best candidate panel from C to add to the permanent panels P as follows:

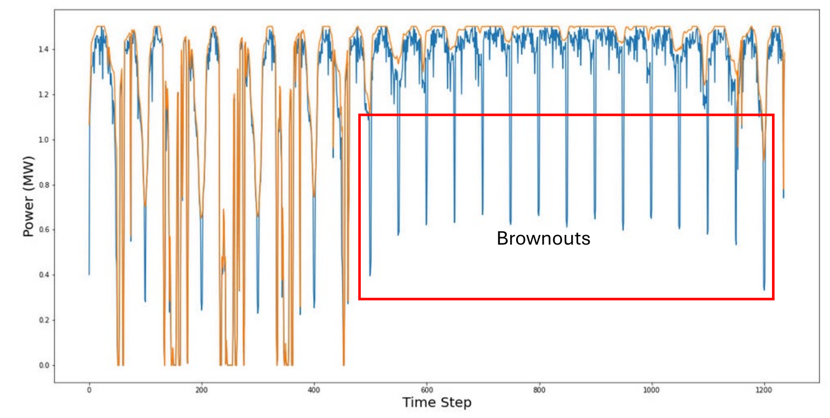
1. For each candidate X in C:
   a. Temporarily apply self-shading of X on P
   b. Compute total energy E=S(P) + S(X)
2. Pick the candidate Xmax which results in the highest energy E
3. Add Xmax to P
   a. Permanently apply shading of Xmax on C
   b. Permanently apply shading of Xmax on P
4. Repeat step 1

Initial Result

Maximizing total Energy







a) The positions of the first 100 panels chosen by maximizing total energy produced during the year 2030, colored by sequence number. Lower numbers contribute more energy.
b) The view of the horizon as seen from the first placed panel (red plus), after the first 100 panels have been placed, maximizing total energy. Note how the alignment of the panels causes much of the shading to occur on already-shaded panels, maximizing the energy at other Sun positions
c) The power produced by the first 100 panels, optimized by total energy, without shading (orange) and with shading (blue) taken into account. The algorithm has naturally found a panel alignment that allows maximum energy productions except for a few limited times (twice a lunar day) when the panels line up with the Sun.

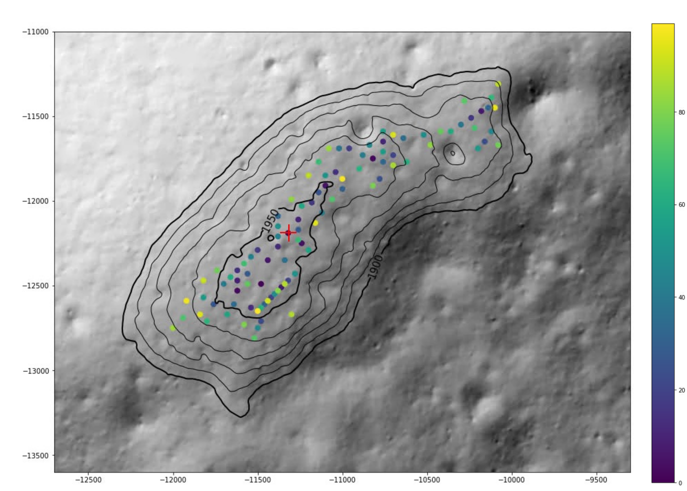
Use of Value

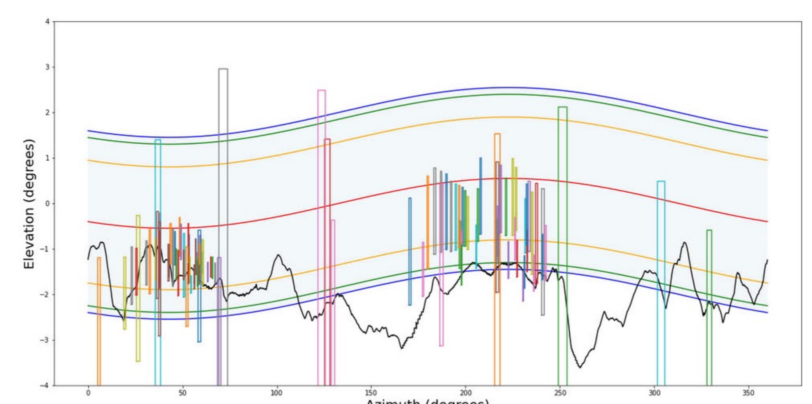
To mitigate the brownouts and obtain a more constant power level over time, one can optimize the configuration not on the integrated power, but on the integrated *value* of the power. This approach rests on the idea that if there is already a lot of power being generated by the grid at a certain moment in time, an additional candidate panel that adds more power at that moment isn't very valuable. But if there is very little power generated at a certain moment in time, any additional candidate panel that can provide power at that moment is valuable.

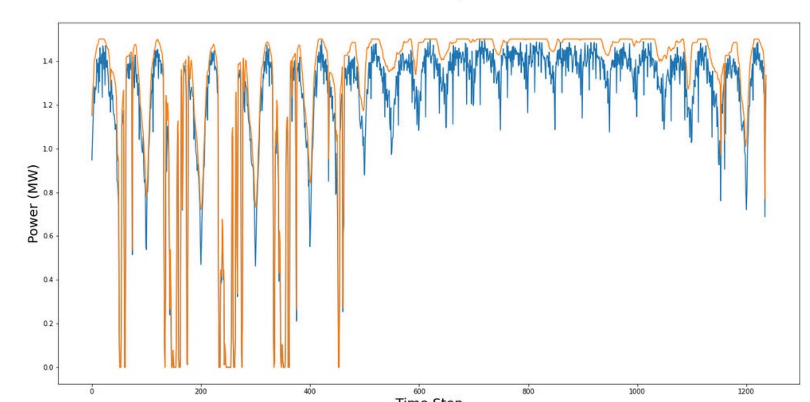
Improved Result – Brownouts Mitigated

Maximizing Value

$$V(A) = \sum_t \ln(I(t)/I_0 + 1)$$

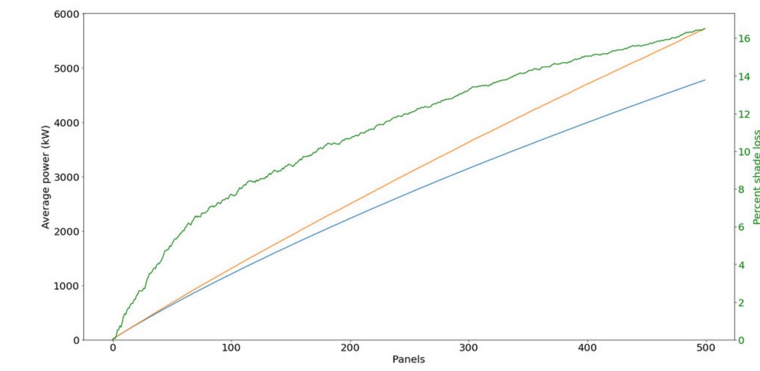




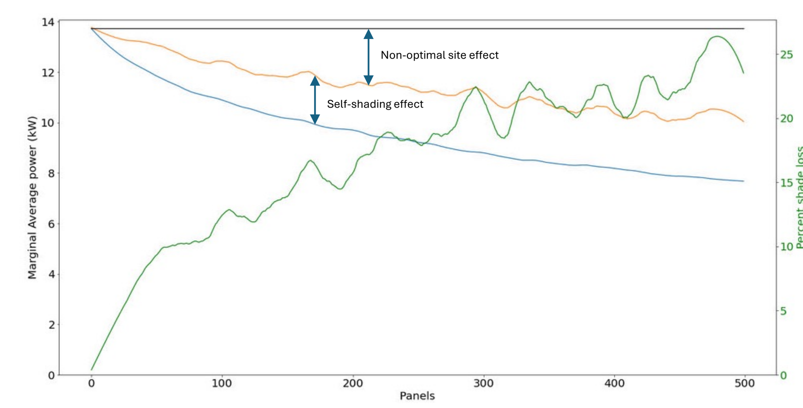


Similar figures to previous but optimizing for value rather than total energy. Note the brownout troughs are gone.

Array Growth Analysis



Average power (MW) over the course of the year 2030 received as the number of VSATs grows according to the sequence in Section 3.3 (blue line), taking account of self-shading. The orange line is the energy if self-shading were ignored (but not horizon shading). The green line is (1-blue/orange) as a percent, the penalty self-shading incurs as the number of panels increases, when placed in the value-optimized sequence.



Similar to Fig. 10 but marginal average power (MW) over the course of the year 2030 received as the number of VSATs grows, with (blue) and without (orange) self-shading. The green line is the percentage loss due solely to self shading. The top black line represents the power production of the first panel for comparison.

Future work

If the individual VSAT panels are reliably mobile on the scales of meters and hours, judicious coordinated movement could further minimize self-shading. The details of such optimization would need to take account of local traversability of the terrain around each panel, and shading interactions between panels. It is a significantly more difficult problem.

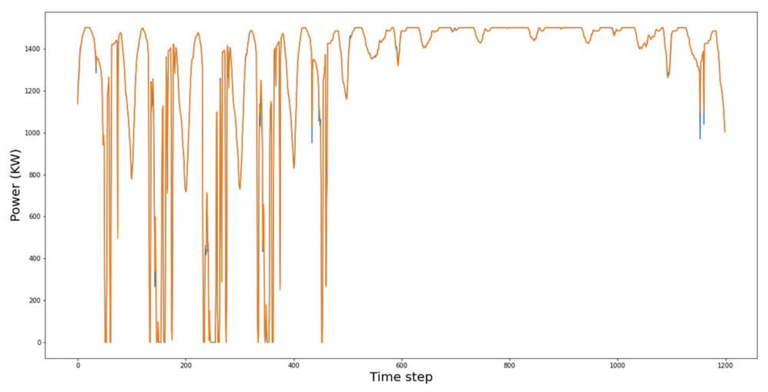


Fig. 6. Power as a function of time, for the year 2030, from the bitmask power computation method (brown line) compared with the raytracing method (blue line) for the case of 100 panels where self-shading is ignored. is shown. The two results are so close they almost overlay.

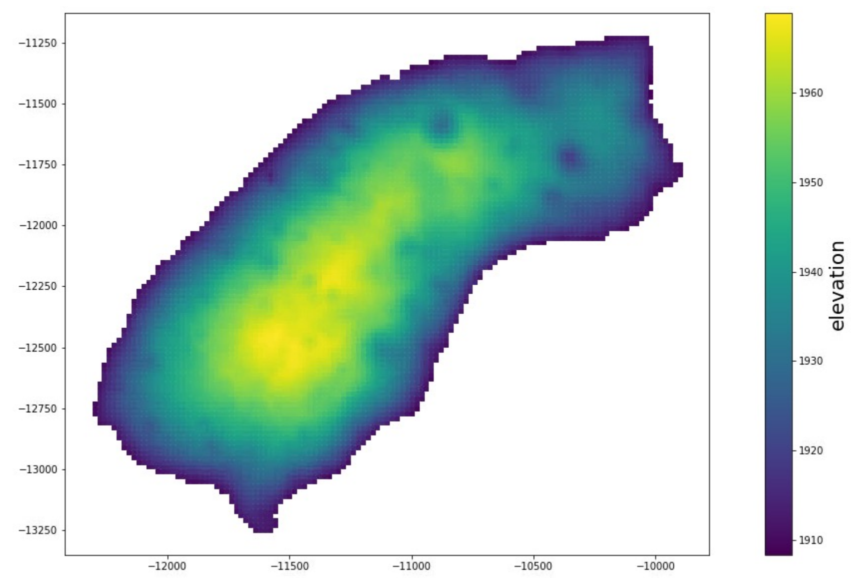


Fig. 7. Candidate VSAT locations, colored by elevation, on a 20m spacing for all points on the Connecting Ridge above 1900m elevation. There are 6166 points in all.

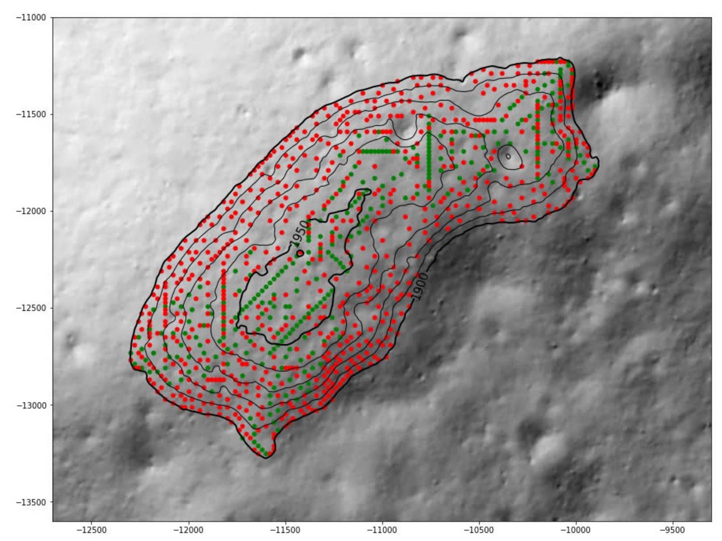


Fig. 12 Distribution of panels 1-500 (green) and 501-1000 (red). There are few green points near the boundary, indicating that this was mostly a large enough area to consider. More than this many panels requires a larger area, so results above about 500 panels are overly pessimistic. That is, a better configuration probably would have been found if candidates at lower elevations had been considered. Thus, the current work is limited to 500 panels.