Balloon-borne Imaging of Polar Mesospheric Clouds

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Polar Mesospheric Clouds (PMCs)

Figure 1: A PMC as observed from the ground. Image from [1].

- PMCs are the highest cloud formations observed on Earth, forming in the mesosphere (50-80km above Earth) above the poles during local winter
- They are composed of very thin collections of suspended ice [2].

Because of their height and sensitivity to changes in atmospheric conditions, observations of PMCs can be used to understand and monitor small-scale dynamics of the high atmosphere.

Challenges of Imaging PMCs

Balloon-borne imaging methods, like most outdoor imaging systems, can suffer from a variety of pathologies, such as

- Dead, or non-responsive pixels
- Lighting gradients due to internal reflections of the camera
- Dust spots on the lens.

These pathologies can change over time, so standard calibration techniques cannot be used.

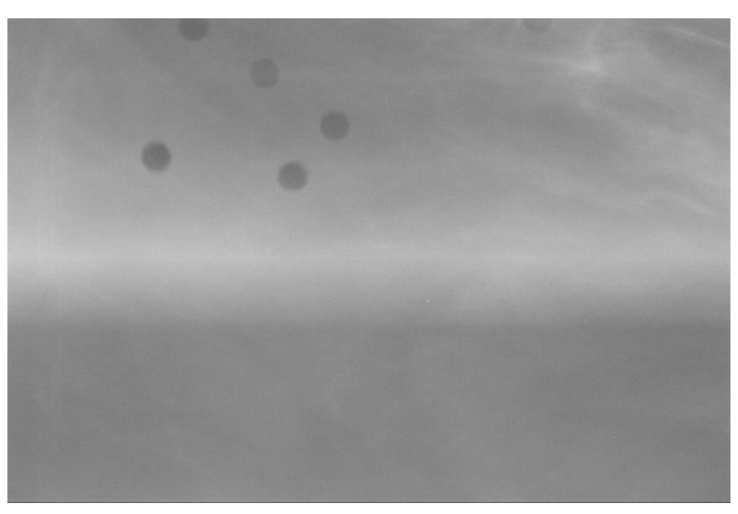


Figure 4: A sample raw image taken by EBEX. This image showcases an lighting gradient, visible dust spots, and PMCs visible in the top right corner. Image by author.

In addition to artifacts present in the images, the enormous amount of images and data taken during a balloon flight makes hand-cleaning images very difficult and time consuming.

Solution: develop automatic image cleaning algorithms that can correct unwanted image artifacts without needing prior camera calibration.

Finding Dead Pixels

- Dead pixels are individual pixels whose recorded value have no correspondence with he amount of light incident upon it.
- If they are not corrected, then they may present computational difficulties for further image processing and analysis.

To find potential dead pixels, a random sample set of images $\{I_k\}^N_{k=1}$ is assembled. A *responsivity matrix* Δ is then calculated, with the (i,j) element being computed as

$$\Delta^{i,j} = \sum_{n=1}^{N-1} |I^{i,j}_{n+1} - I^{i,j}_{n}|$$

A perfectly dead pixel at position (i,j) will thus correspond to a value of $\Delta^{i,j} = 0$, while a responsive pixel will correspond to larger value.

An ad-hoc threshold can be used to ensure that pixels must have a responsivity above a certain value to be considered in analysis.

References

- [1"Clouds 101 Special: Noctilucent Clouds(NLC)". Simply-Selma. Retrieved 2 July 2018.
- [2] Thomas, GE; Olivero, J (2001). "Noctilucent clouds as possible indicators of global change in the mesosphere". Advances in Space Research. 28 (7): 939–946.
- [3] "Balloon-Borne Telescope Seeks Out Elusive Big Bang Signal". Space. Retrieved 2 July 2018.
- [4] Chapman, D (2015). EBEX: A Balloon-Borne Telescope for Measuring Cosmic Microwave Background Polarization (Doctoral Thesis). Retreived from Columbia University.

Balloon-borne Observations of PMCs

Figure 2: An image of the EBEX balloon prior to launch from Antarctica. Image from [3]

- EBEX was a cosmological balloon-borne experiment that flew above Antarctica in late 2012. It flew for 11 days at an altitude of 35km.
- Onboard cameras designed to identify overhead stars for orientation serendipitously captured approximately 20,000 high-resolution images of PMCs

The high altitude of EBEX allowed the captured images to have spatial resolution up to 100 times better than ground-based observations and up to 1000 times better than satellite-based observation .

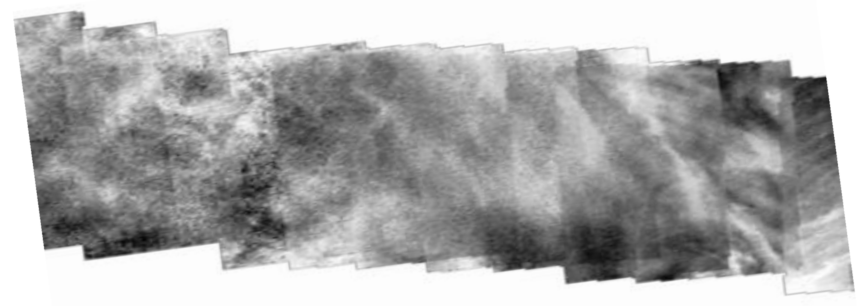


Figure 3: An example of a multi-image cloud feature stitched together using orientation data from each image. Image modified from [4].

- EBEX was also able to use the orientation of the camera relative to the sky to reconstruct multi-image structures, and monitor cloud evolution over time.
- This discovery led to the PMC-Turbo mission, a balloon-borne imaging system designed specifically to observe PMCs and their evolution

Correcting Image Gradients

- The effects of an uneven lighting gradient can be modelled by treating each image as a matrix $\boldsymbol{I} \in \mathbf{R}^{m \times n}$
- Each image is thus the combination of a "true image", which may still have things like dust spots present, and a gradient image:

$$I(x,y) = I_{true}(x,y) + g(x,y)$$

- The gradient image ***g(x,y)*** can be estimated by assuming that the medians of each horizontal row of I_{true} should be approximately equal. This suggest that any low-frequency trend in the medians of horizontal rows is due to a lighting gradient.
- Approximating the gradient as a piecewise linear function, the gradient image can be estimated via a least-squares fitting of the plot generated by plotting the median value of the row ***I(•,y)*** against the value of *y*.

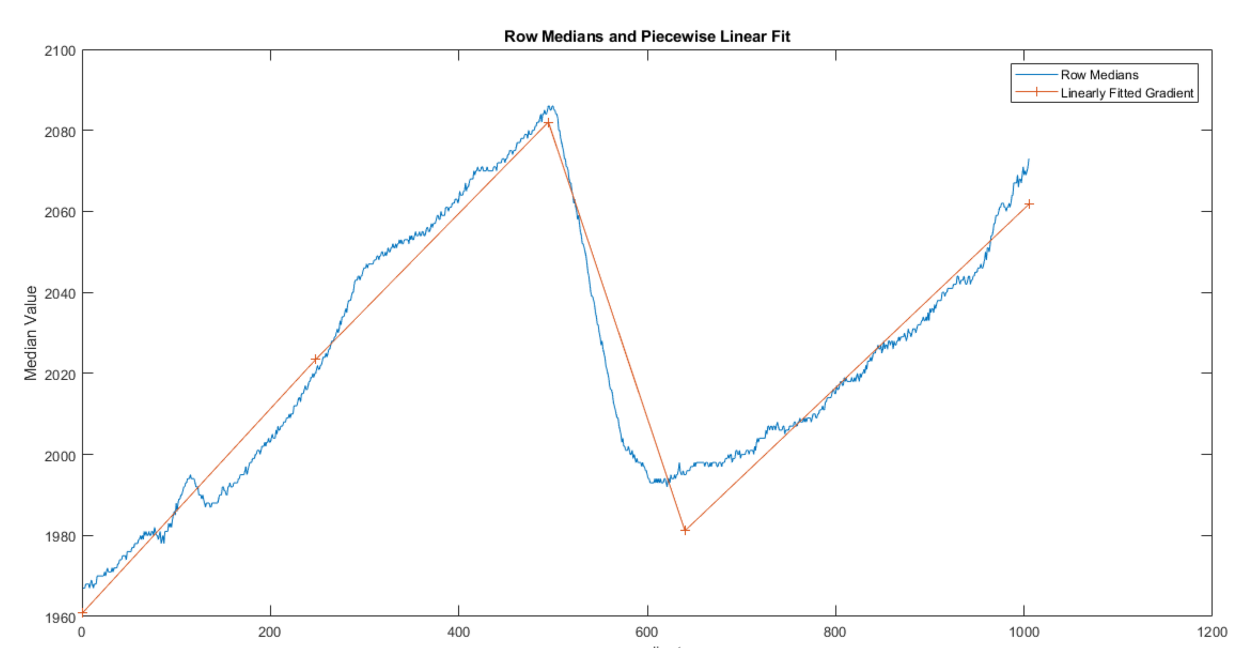
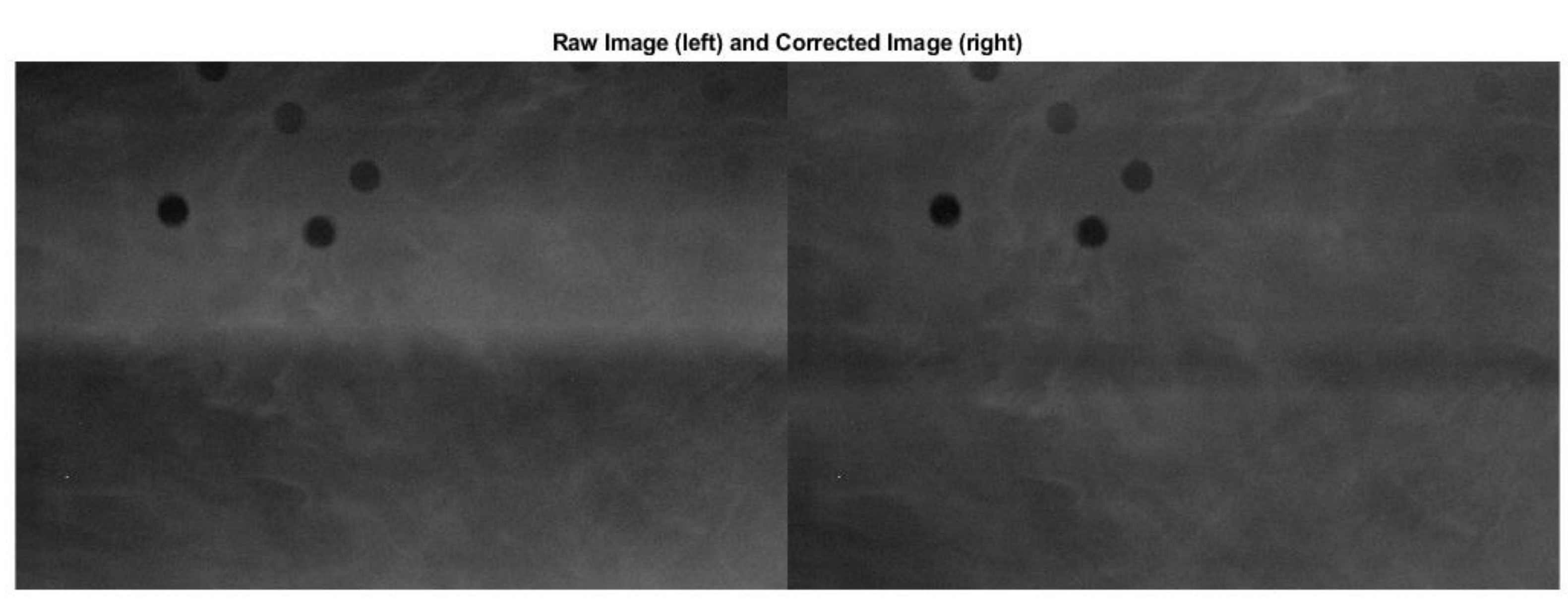


Figure 5 (Left): A plot showing a given image's row medians plotted against the row's *y*-coordinate. The red line shows the least-squares fitted piecewise linear approximation of the illumination gradient.

Figure 6 (Below): The raw image and the image constructed by subtracting the approximated gradient.



Detecting Dust Spots

Dust spots are represented in the image data as region of locally attenuated signal. That is, in these regions the recorded signal can be represented , for some real number $\alpha \in [0,1]$ as

$$I(x,y) = \alpha \times I_{true}(x,y)$$

The change in the signal is very abrupt, which would suggest that the boundaries of the dust spots are local extrema of the image's gradient, $\nabla I(x,y)$. Furthermore, since the position of the dust spots does not change between images, those pixels which are local maxima the most frequently can be considered candidates for the pixel boundaries of dust spots.

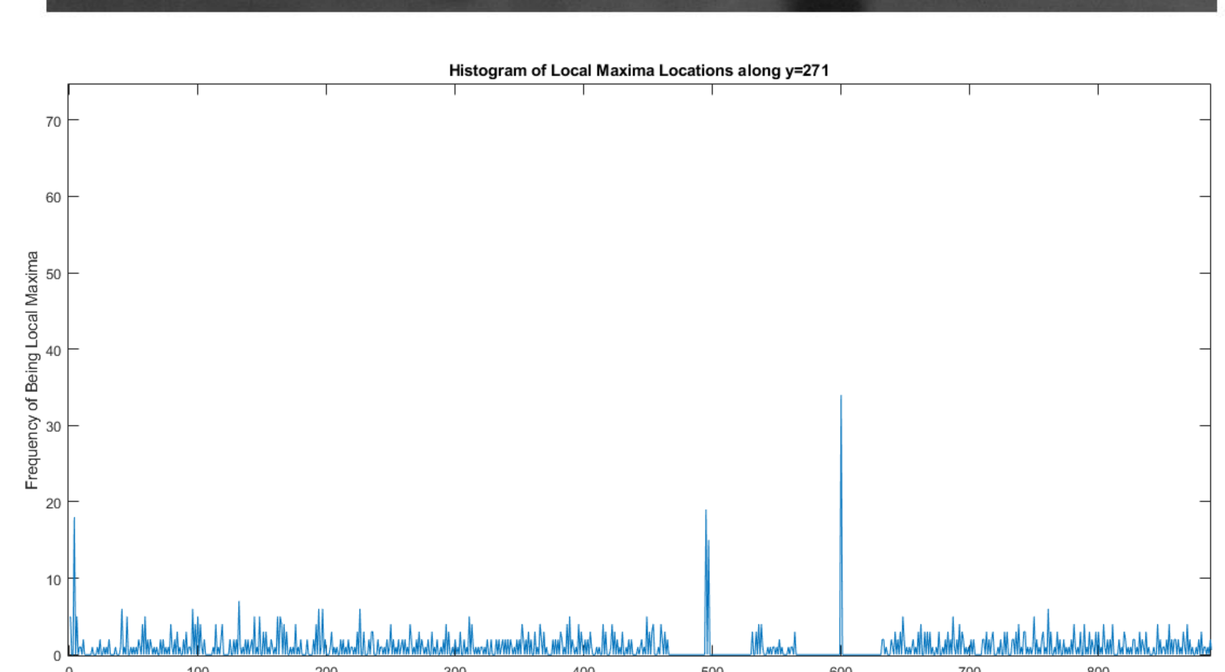


Figure 7 (Top): A small section of the image showing the horizontal row across which the image gradient was computed for 35 images. The line is at height y=271.

Figure 8 (Below): A histogram showing the x-coordinates of local maxima of the image gradient across 35 other images. Note the two large spikes, corresponding to the edges of the dust spot visible in Figure 7.