Fully Controlled 6 meters/pixel Mosaic of Mars' South Pole & Equator from Mars Reconnaissance Orbiter Context Camera Images

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Header Background: Viking MDIM 2.1 (left) fading into CTX mosaic from this work (right)

Abstract: Our Work in Brief

We developed a set of Python tools that interface with USGS's *Integrated Software for Imagers and Spectrometers 3* (*ISIS3*) in order to create high-quality, **fully automated**, **relative** control networks (no ties to ground sources) of CTX data [1]. CTX data are currently the most consistent, highest resolution, near-global imagery of Mars. We divided Mars into 480 regions and have progressed in creating the shown relative networks for an equatorial band (±7.5°N, 64 regions) and the south pole Mars Chart #30 (south of –65°N, 16 regions).

Our code can generally control each region on a typical modern computer in ~1 day, though regions with significant overlap (e.g., the poles, or landing sites) can take longer (up to ~3 weeks). Further, our workflow allows for the **full control** (or absolute control) of these images with about 1 hour of manual effort, per region. Once adjacent regions are completed, they are combined for a group solution.

With this workflow, we can **fully control all CTX images** in a region, export **updated SPICE data**, and from the controlled images, produce **fully controlled mosaics**. A further semi-automated workflow reduces effort in ordering images for a mosaic, and it automatically equalizes images to create an aesthetically useful product. We are completing our efforts in these regions now and plan to release the south polar mosaic and SPICE data to PDS, pending acceptance of a peer-reviewed manuscript.

Completed Regions

During development of our code, we have created fully controlled mosaics for several regions of Mars.

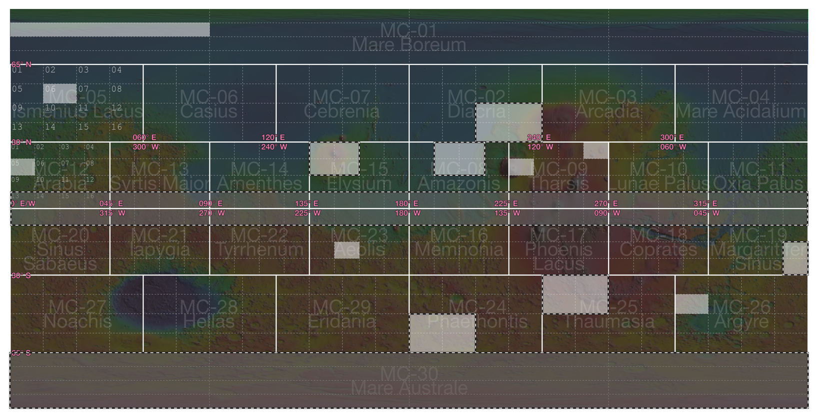


Figure 1: MOLA shaded relief of Mars with Mars Charts (01–30) indicated. Fixed-width numbers and thin dashed lines indicate how the Charts are further sub-divided. Light grey shaded regions indicate completed areas, and dark grey is in final construction (didn't quite finish for LPSC). Regions bordered by thicker black-white dashed lines indicate group solutions. The equatorial region is 13.1% of Mars, and the south pole is 4.7%.

Workflow

This flow chart illustrates a summary of our Python workflow, interfacing with *ISIS3* tools.

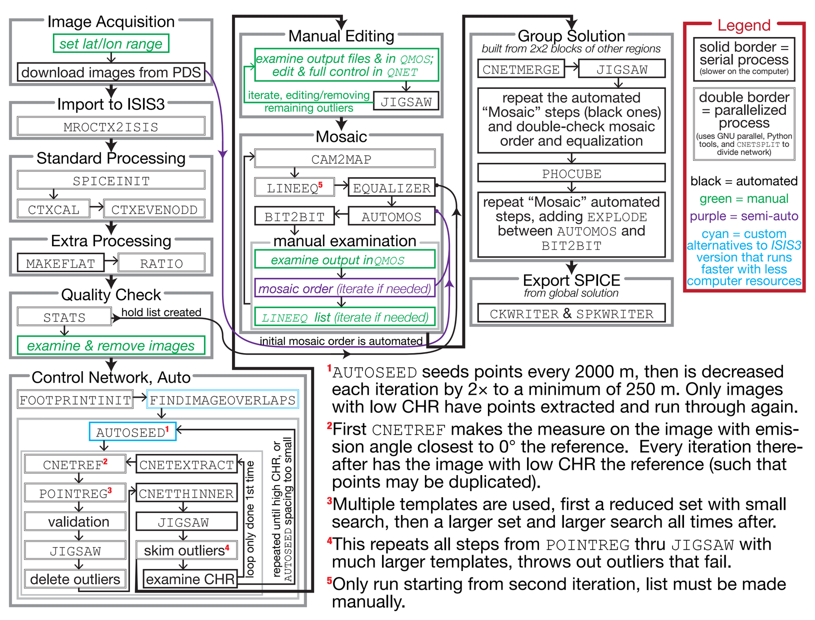


Figure 2: Overview of our workflow, emphasizing automated versus manual versus semi-automated steps. ISIS3 *programs are noted in* `fixed-width fonts`*. The bulk of time, both real-time and CPU-time, is spent in the "Control Network, Auto" step, which is highly iterative. The bulk of manual time is spent in "Manual Editing" and "Mosaic" to create the absolute control points and iterate on mosaic order and equalization to produce aesthetically useful mosaics.*

Good Control Point Coverage

Our iterative automated process emphasizes the need for good spatial coverage of control points across all images. This is accomplished by progressively finer automated seeding of points, but on progressively fewer images, as needed, down to a minimum at which time it is faster to add a few remaining points manually (if needed, if possible).

Near ~65°S is the worst current coverage with some of the largest seasonal differences at CTX scale (*e.g.*, dust devil tracks) with few persistent features. Our code does have trouble in these areas such that manual effort is needed more here than elsewhere. However, the automated steps significantly reduce the needed manual effort, even in these areas.

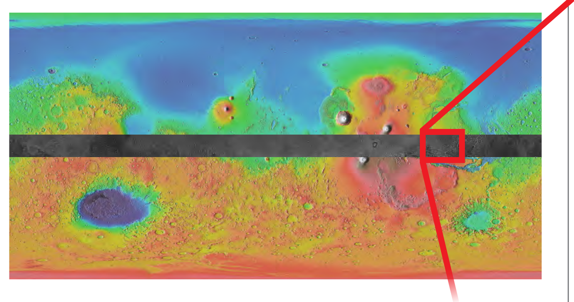
Low Residuals

(small deviations from the solution)

`JIGSAW` solves the control network's points for the best solution, modifying spacecraft and camera data. Residuals from that solution are always present. Our code applies a "skimmer" that removes the largest residual points, tries to re-match them with different parameters, and re-runs `JIGSAW`. It repeats, again skimming the largest residuals (or removing those points if they were already tried the last iteration).

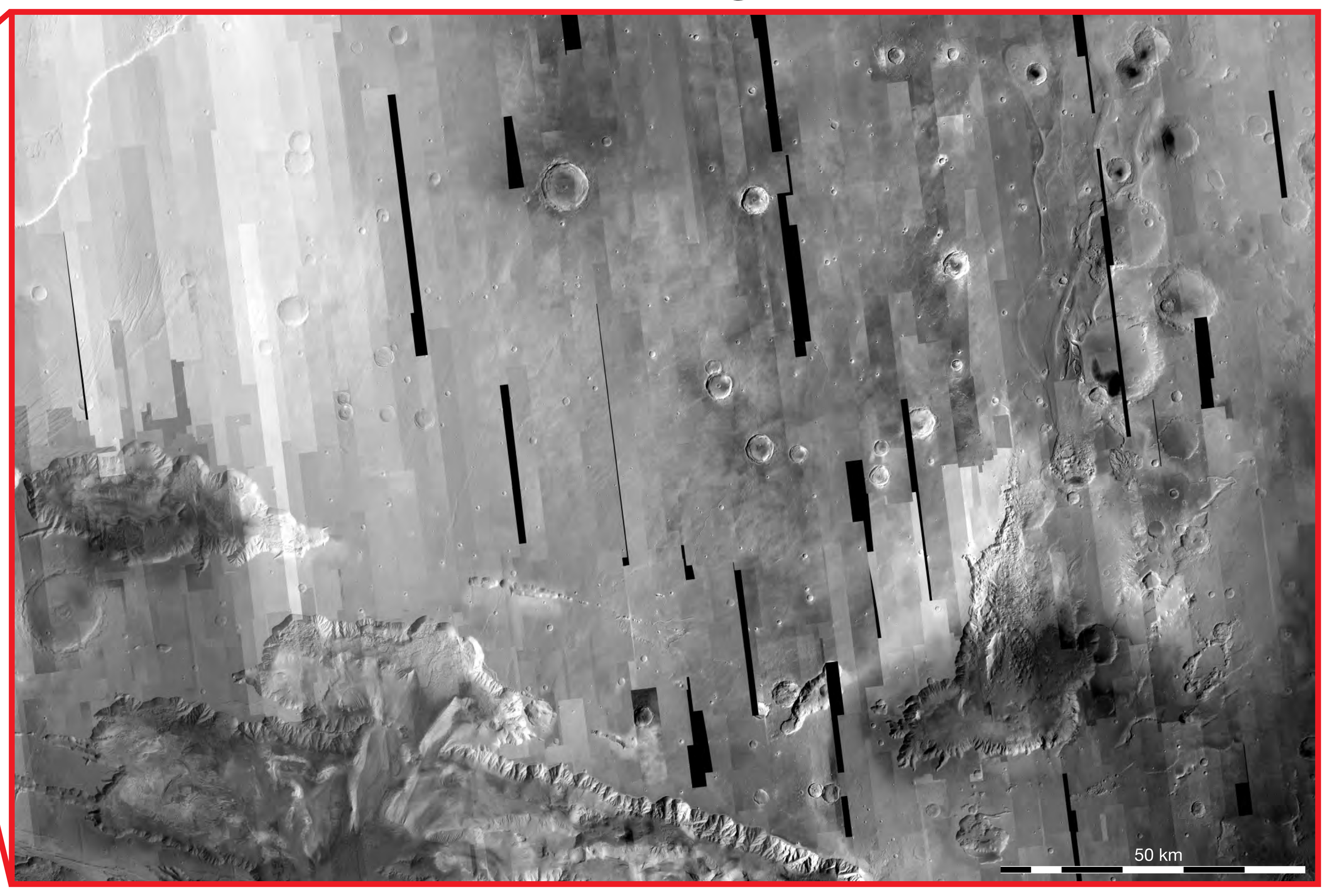
The threshold at which our code stops and considers the network finalized is when the 99.99[th] percentile of the residuals of the control points is ≤1 pixel.

Equatorial Progress



MOLA colorized, shaded relief map (background) with Viking MDIM v2.1 overlaid for ±7.5°N. Thick red rectangular area indicates large region that is shown in this panel.

All equatorial regions have run through our automated code. During this process, the code has been completely re-written, twice. Therefore, we are only showing a part of this region that has been run through with our latest code, and show another part on our large poster. The region shown here spans 4 of our 480 regions.



Large Image: This shows 4 of the 64 equatorial regions, spanning 281.25°–303.75°E, –7.5°–+7.5°N, approximately 0.82% the surface area of Mars.

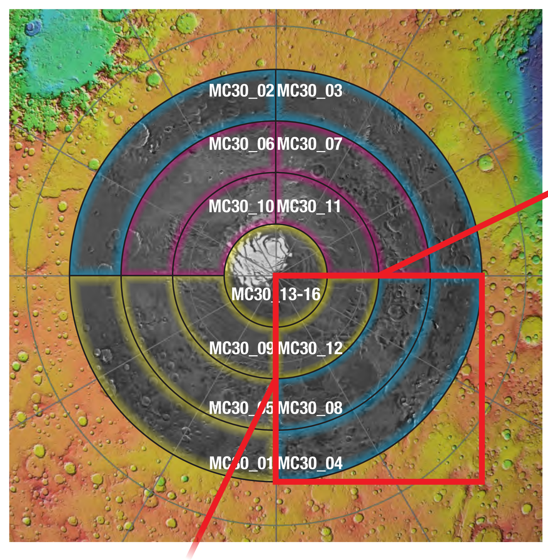
For this region, we have done extremely preliminary brightness / tone-matching and not manually adjusted the image order. There is also an overall gradient that we can remove with further processing. The mosaic is still aesthetically useful, even if it is not cosmetically perfect.

Importantly, across all image seams, features are properly aligned and matched, and they are at the correct latitude and longitude on Mars' surface.

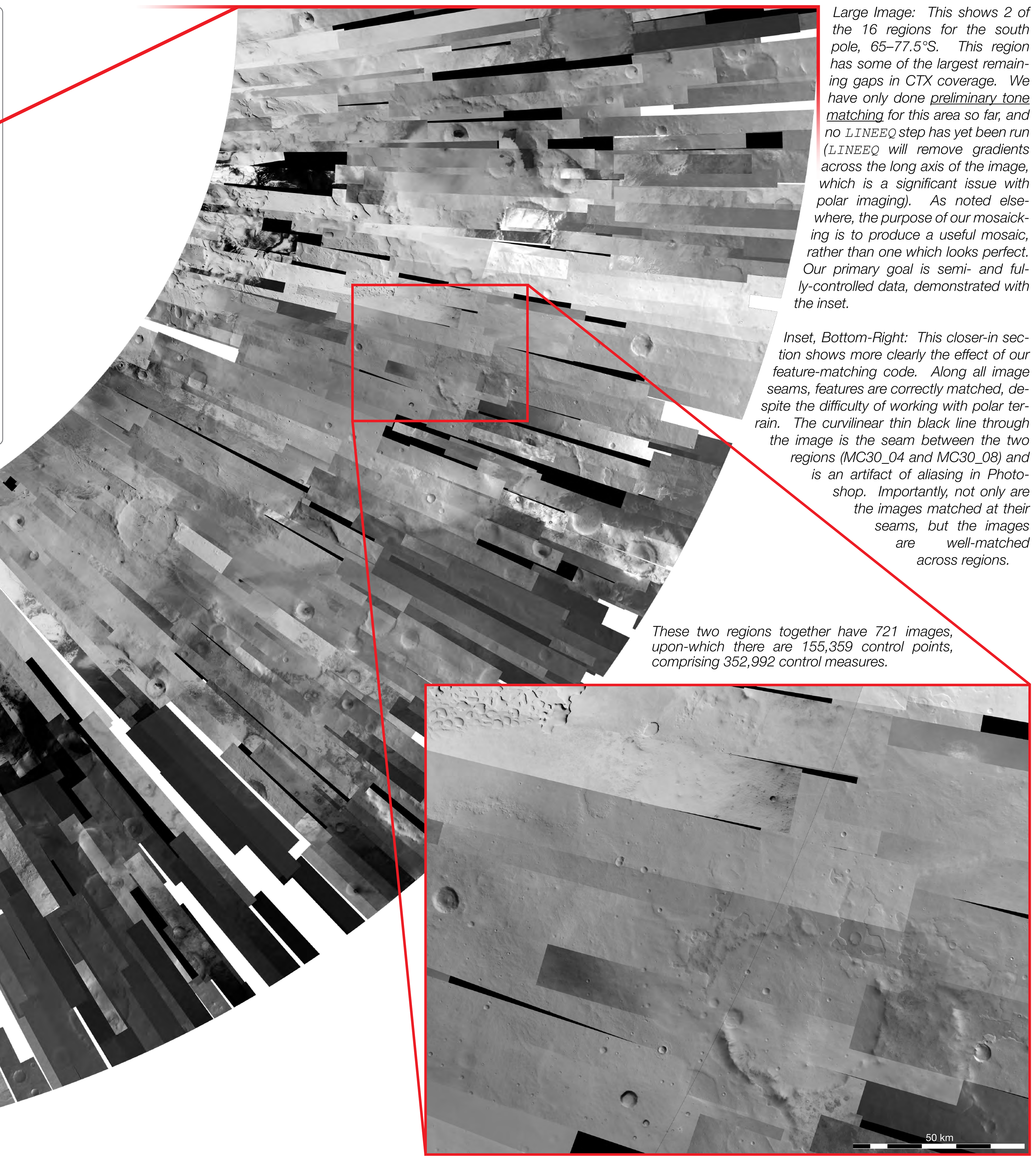
Additionally, even though this mosaic comprises four distinct regions that were controlled separately, our group solution for the four means that the seams are invisible and features match across the regions. This highlights the ability of our automated control process.

These four regions together have 1292 unique images (images on edges are duplicated in the different regions, helping with control), upon-which there are 268,788 control points, comprising 1,168,729 control measures.

South Polar Progress



MOLA colorized, shaded relief map (background) with Viking MDIM v2.1 overlaid south of 65°S. Thick red rectangular area indicates large region that is shown in this panel. Magenta areas have yet to be started, yellow regions are currently running on our facilities, and cyan regions have been completed.



Large Image: This shows 2 of the 16 regions for the south pole, 65–77.5°S. This region has some of the largest remaining gaps in CTX coverage. We have only done preliminary tone matching for this area so far, and no `LINEEQ` *step has yet been run (*`LINEEQ` *will remove gradients across the long axis of the image, which is a significant issue with polar imaging). As noted elsewhere, the purpose of our mosaicking is to produce a useful mosaic, rather than one which looks perfect. Our primary goal is semi- and fully-controlled data, demonstrated with the inset.*

Inset, Bottom-Right: This closer-in section shows more clearly the effect of our feature-matching code. Along all image seams, features are correctly matched, despite the difficulty of working with polar terrain. The curvilinear thin black line through the image is the seam between the two regions (MC30_04 and MC30_08) and is an artifact of aliasing in Photoshop. Importantly, not only are the images matched at their seams, but the images are well-matched across regions.

These two regions together have 721 images, upon-which there are 155,359 control points, comprising 352,992 control measures.

The polar regions present significant challenges, from seasonal processes, to poor quality images, to both significant gaps in imaging in some areas to >100 images for a given pixel in other areas. We have mitigation strategies built into our workflow, but it still takes significant resources to run a single region (1/16th of the area). Coupled with re-writing our code base to make it more efficient, twice since our abstract was submitted, we have not yet completed the polar area. Instead, we present progress here and indicate what regions are completed, are currently running on our computer resources, and have yet to be started. With our latest code base, we expect completion by early summer 2019, at which point the work will be submitted to peer-review in *Earth & Space Science* and, if accepted, the mosaics and SPICE data will be released to PDS.

Mosaic Order

Mosaic order is initially set in the image selection step. Our code assigns a score from 0 to 1 based on how far the parameters are from what we set as the ideal: Best pixel scale, 0° emission angle, 70° incidence angle, and L_s = 90° (northern spring).

The scores are then summed for each image and initial order is set by the score order.

Mosaic order is modified manually during the "Mosaic" phase if necessary, typically requiring ~1% of the image order to be modified, based almost entirely on low signal-to-noise.

Equalization

`MAKEFLAT` and `RATIO` produce empirical flats to remove the brightness "smile" across CTX images. `EQUALIZE` is used to create an evenly illuminated mosaic. We use `LINEEQ` on manually selected images to remove vertical brightness differences; this must be manual because some brightness variations are true albedo differences and should be retained.

Figure 5: Example of poor mosaic order and equalization to an "aesthetically useful" version, also showing the corrected pointing.

Updated SPICE Data

Upon completion of a "group" solution, updated SPICE data can be output using *ISIS3*'s `CKWRITER` and `SPKWRITER`. We will provide updated SPICE data for all images covering all areas in published regions.

Future Mars Work

We plan to fully control all available, usable CTX data. Such a task is large, even with our mostly automated process, such that we are pursuing potential funding sources. This work complements the CalTech group's seamless global mosaics and does not compete.

Future Work on Other Bodies

Our workflow was developed specifically for CTX data, which are taken under almost ideal conditions: Similar times of day, a fairly stable imager, similar pixel scales, similar emission angle, and same wavelength. Modifying our code to operate with data that do not meet those constraints is also an area we are pursuing, with promising initial, very preliminary results for *MESSENGER* data of Mercury and *Cassini* data of Saturn's moons.

References & Acknowledgments

[1] Malin, M.C., *et al.* 2007. Context Camera Investigation on board the Mars Reconnaissance Orbiter. J. Geophys. Res. 112, E05S04–25. doi:10.1029/2006JE002808

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