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Supporting Information for

Revealing the early ice flow patterns with historical Declassified Intelligence Satellite Photographs back to 1960s

Shujie Wang[1], Hongxing Liu[12], Bailang Yu[2], Guoqing Zhou[3] and Xiao Cheng[4]

[1]Department of Geography, University of Cincinnati, Cincinnati, Ohio, USA.

[2]Key Laboratory of Geographic Information Science, Ministry of Education, East China Normal University, Shanghai, China.

[3]Guangxi Key Laboratory for Geospatial informatics and Geomatics Engineering, Guilin University of Technology, Guilin, China.

[4]State Key Laboratory of Remote Sensing Science, College of Global Change and Earth System Science, Beijing Normal University, Beijing, China.

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Introduction

This auxiliary material contains the discussion about the lens distortion of ARGON KH-5 camera (Text S1), the equations to correct the geometric distortions induced by the Earth curvature effect and the relief displacement (Text S2), the geolocation accuracies of the other two methods (Text S3), the image data preprocessing for velocity derivation (Text S4), the case study area (Figure S1), the two Landsat-3 MSS scenes used for velocity mapping (Figure S2), the orthorectification results of the ARGON images (Figure S3), and the error statistics of the geolocation accuracy (Table S1).

Text S1. Lens distortion of ARGON KH-5 camera

Radial lens distortion can be approximated by a polynomial function if the coefficients are provided in the camera calibration report. Unfortunately, the lens distortion parameters for the ARGON KH-5 camera are unknown. Nevertheless, the impact of lens distortion on ARGON image orientation may be minimal or negligible according to the relevant declassified documents. The document 'TECHNICAL EXPLANATION OF PROJECT ARGON Orbital and Camera Requirements and Data Reduction Procedure' (Ref: 2 C 0037) archived in the National Reconnaissance Office (NRO) records the distortion (radial & tangential) specification for the KH-5 camera is 0-6 microns. According to the NRO-declassified document 'HEXAGON (KH-9) MAPPING CAMERA PROGRAM AND EVOLUTION' and other related records, the KH-5 camera used the Baker-Developed lens Geocon. In the patent documents about the wide angle photogrammetric lens systems Geocon, Baker pointed out that the expected distortion residuals of 3 inch focal length lens did not exceed 5 microns anywhere in the field. The ARGON KH-5 images have nominal ground resolution of 140 m, corresponding to ~33 microns on the photograph. The positional error induced by lens distortion is expected to be negligible. In addition, the primary distortion component, the radial lens distortion, increases radially from the principal point to the four corners of the photograph. The majority of our focused study area is located at the center of the photographs, and therefore, the influence of lens distortion is considered minimal.

Text S2. Corrections for the Earth curvature effect and the relief displacement

As the frame photographs captured by ARGON camera system have quite large ground coverage, the geometric distortion caused by Earth curvature effect needs to be addressed. The Earth curvature effect can be calculated by equation (1) [*Moffitt and Mikhail*, 1980]

$$\Delta r = \frac{r^3 H}{2Rf^2} \tag{1}$$

$$R = \frac{a(1-e^2)}{(1-e^2\sin^2\Phi)^{\frac{3}{2}}} \tag{2}$$

$$e = \frac{a^2-b^2}{a^2} \tag{3}$$

where Δr is the inward radial displacement to be corrected due to Earth curvature, r is the radial distance from the principal point, H is the flying altitude, R is the Earth radius, f is the camera focal length. a is the semi-major axis of the ellipsoid, b is the semi-minor axis of the ellipsoid, Φ is the mean latitude. For our study area, the Earth radius was estimated to be 6,378,207.8 meters using the equation (2), with reference to the WGS-84 ellipsoid. Given the orbital altitude H of 322 km, Δr approximately equals to 4.35 r^3 based on equation (1). On a 4.5-inch photograph, the displacement caused by Earth curvature at the corner points is about 2295 microns, corresponding to the ground distance of 9.8 km.

The relief displacement can be corrected using a digital elevation model [*Moffitt and Mikhail*, 1980]:

$$\Delta r' = \frac{rh}{H} \quad (4)$$

where $\Delta r'$ is the outward radial displacement due to topography, r is the radial distance from the principal point, h is the topographic height, and H is the flying altitude.

Text S3. The geolocation accuracies of polynomial transformation method and thin plate spline method

Table S1 summarizes the error statistics for the accuracy assessment. The second-order polynomial transformation method has overall RMSE of 214.7 m (146.7 m in X, 156.7 m in Y), and of 539.8 m (289.2 m in X, 455.7 m in Y) comparing with the WorldView images and the LIMA, respectively. The thin plate spline method has overall RMSE of 133.2 m (112.3 m in X, 71.6 m in Y), and of 225.3 m (115.2 m in X, 193.4 m in Y), respectively. Although the thin plate spline method has better performance than the polynomial transformation method, the RMSEs of both methods are significantly larger than that of the camera model. This indicates that these two empirical methods are not adequate in correcting geometric distortions in ARGON images, and the rigorous camera model with bundle block adjustment is the most suitable with a set of high-quality GCPs derived from the WorldView imagery.

Text S4. Image preprocessing

To ensure the image matching accuracy and reliability, several preprocessing procedures were performed, including image co-registration, noise filtering and image enhancement. The two Landsat MSS images were co-registered to the orthorectified ARGON images, and the overall RMSE of the co-registration was estimated to be 54.1 m. An adaptive Wiener filter [Jin et al., 2003] with a 5×5 window was applied to the ARGON images to reduce the film grain noise [*Zhou and Jezek*, 2002]. The Landsat-4/5 TM images acquired in 1986 and 1988 have spatial resolution of 30 m, and have been also co-registered. To enhance the image contrast, we used a water mask to remove the ocean part on the images, and segmented the image pairs into multiple pieces. For each segmented image pair, we enhanced the image contrast by stretching the histogram. This localized image stretching can highlight the edge features of the low-contrast ice surface features. We performed image matching procedure for each segmented image pair.

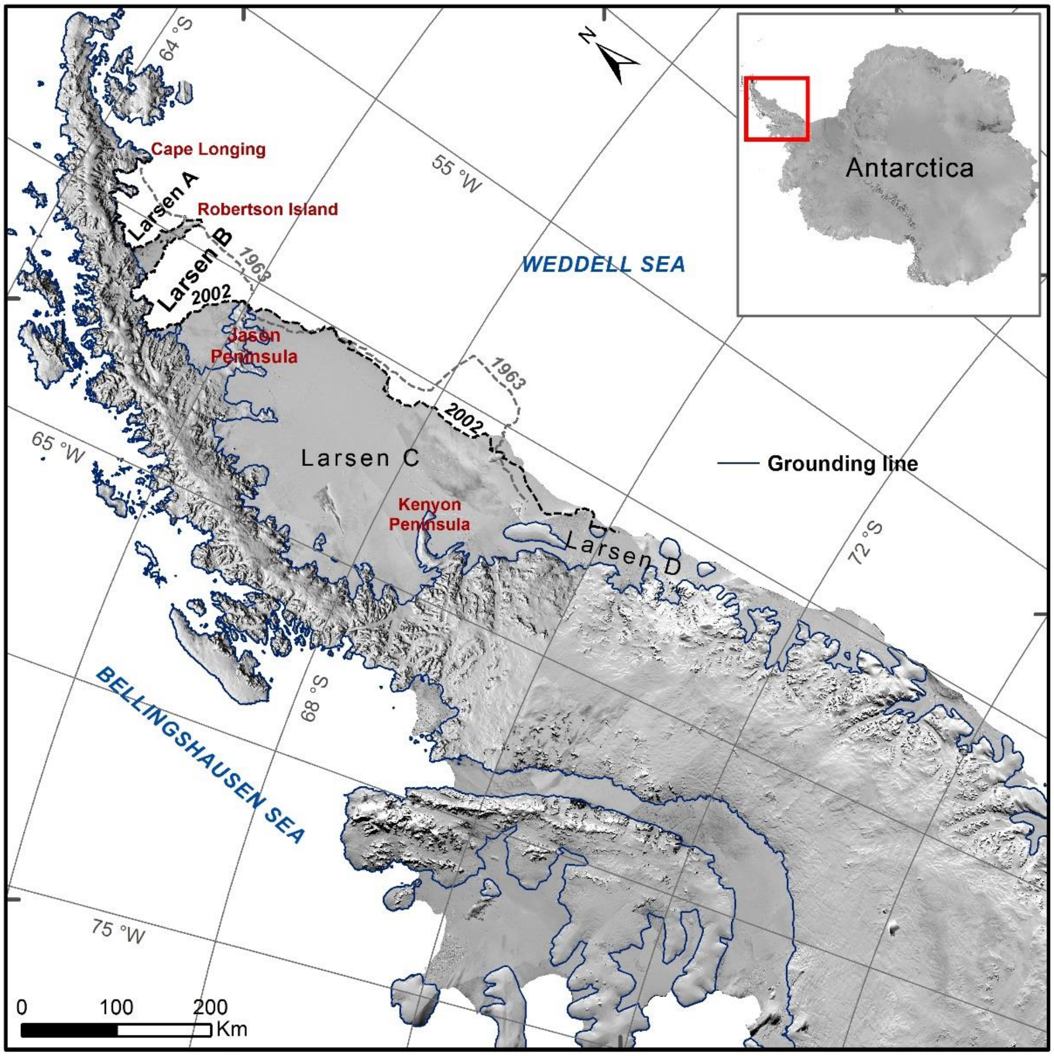

Figure S1. The Larsen Ice Shelf. The background image is the pan-sharpened red band image of the Landsat Image Mosaic of Antarctica (LIMA) [*Bindschadler et al.*, 2008]. The grounding line is from the MEaSUREs Antarctic Grounding Line [*Rignot et al.*, 2011]. The two dash lines show the partial coastlines of Larsen Ice Shelf in August 1963 and December 2002, respectively. The projection is polar stereographic projection with reference to WGS-84 ellipsoid.

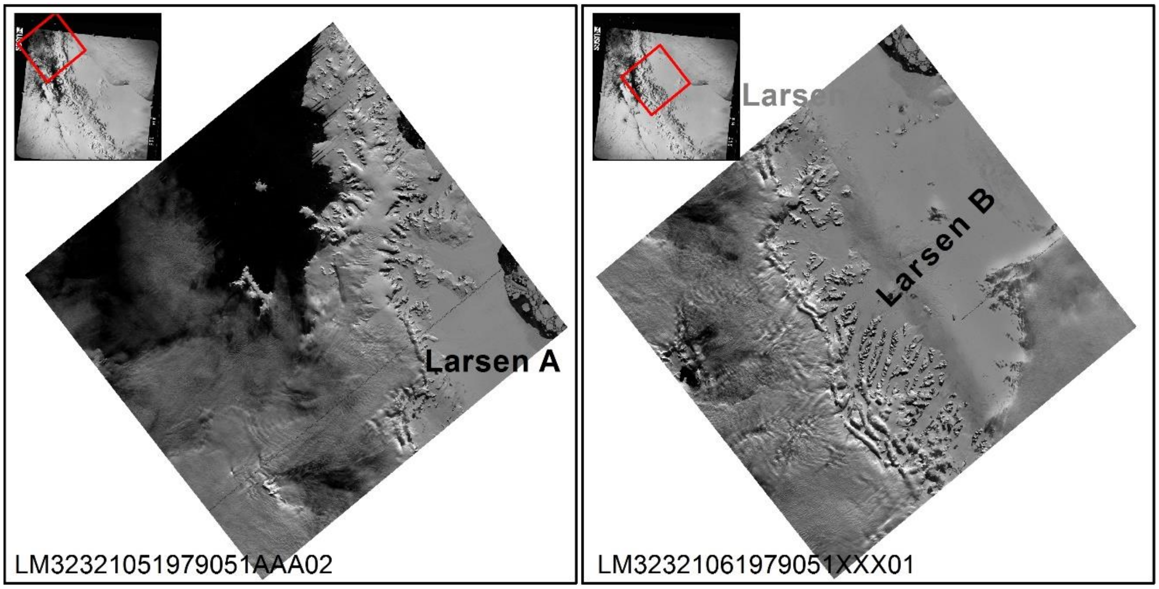

Figure S2. Two Landsat-3 MSS scenes (near infrared band) acquired in 1979

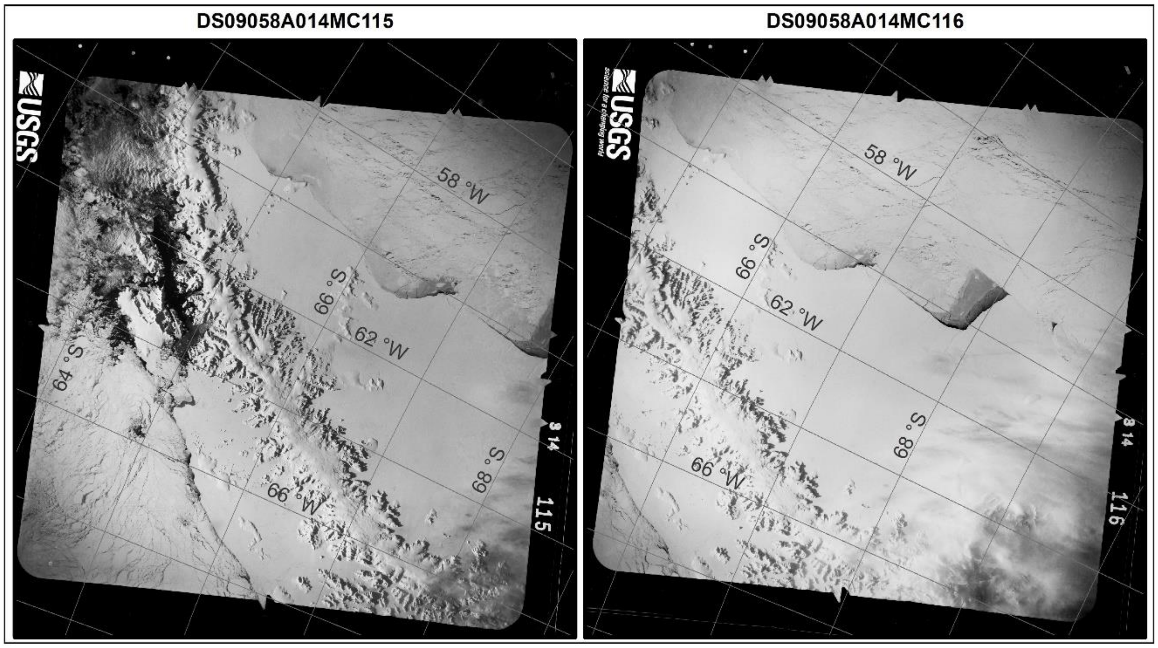

Figure S3. Orthorectified ARGON KH-5 images

Table S1. Horizontal geolocation accuracy assessment of the orthorectified images

	CPs from WorldView			CPs from LIMA		
	Overall	x	y	Overall	x	y
Rigorous camera model	98.8	73.6	66.0	114.8	85.8	76.3
Polynomial transformation	214.7	146.7	156.7	539.8	289.2	455.7
Thin plate spline	133.2	112.3	71.6	225.3	115.2	193.4

CPs: checkpoints; unit: meter

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