

# The 2017 Catastrophic Subsidence in the Dalk Glacier: Unmanned Aerial Survey and Digital Terrain Analysis

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**Abstract**—We present the first results from a study of the 2017 catastrophic subsidence in the Dalk Glacier, East Antarctica using an unmanned aerial system (UAS) and UAS-derived DEMs. The subsided portion of the Dalk Glacier and adjacent territory was surveyed in two flights, before and after the collapse. The survey was performed by Geoscan 201, a small flying-wing UAS. Aerial images have an average resolution of 6 cm. Using Agisoft PhotoScan software, we generated two DEMs with a resolution of 22 cm related to the pre- and post-collapsed glacier surface. To model the pre-collapsed subglacial cavern, one DEM was subtracted from the other. Finally, we discuss a probable mechanism of the catastrophic subsidence.

## I. INTRODUCTION

Unmanned aerial systems (UASs) are increasingly used in science and industry. In particular, UAS-derived imagery is utilized for producing high-resolution DEMs, which are then applied to model dynamics of slope, coastal, and fluvial processes, to reveal fine geological features, etc. [1].

The use of UASs may significantly facilitate the work of researchers in severe conditions of mountain glaciers and ice sheets (see a review of UAS application in glaciology — [2]). In Antarctica, UAS-derived DEMs are used for geomorphological studies and surface evolution analysis [3]. Extreme temperature and meteorological conditions of Antarctica make special demands on the characteristics of UASs, installed equipment, and aerial surveying techniques [4].

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Here we present the first results from a study of the 2017 catastrophic subsidence in the Dalk Glacier, East Antarctica using unmanned aerial survey and UAS-derived DEMs.

## II. STUDY AREA

The study was conducted in the Larsemann Hills, East Antarctica (Fig. 1). The Larsemann Hills are ice-free, low rounded hills with an area of about 40 km<sup>2</sup> located on the south-eastern coast of the Prydz Bay, Princess Elizabeth Land. Larsemann Hills is one of the Antarctic Specially Managed Area [5]. There are three year-round operated polar stations in this area: Progress (Russia), Zhongshan (China), and Bharati (India).

The Dalk Glacier is a 15-km long, polar outlet glacier draining into the south-eastern part of the Prydz Bay east of the Larsemann Hills. On January 30, 2017, a rare natural catastrophic phenomenon occurred: a wide depression formed abruptly in the north-western margin of the Dalk Glacier, at the coordinates 69°23'58" S, 76°24'49" E.

## III. METHODS

### A. UAS characteristics

The survey was performed by Geoscan 201 (Fig. 2), a flying-wing UAS with a wingspan of 2.3 m and a takeoff weight of 8 kg, launching by a catapult and landing with a parachute [6]. It can be used at air temperature of ±40°C and wind speed up to 15 m/s. Geoscan 201 has an electric motor; the flight duration is up to 3 hrs with a cruising speed of 110 km/h; maximal flight

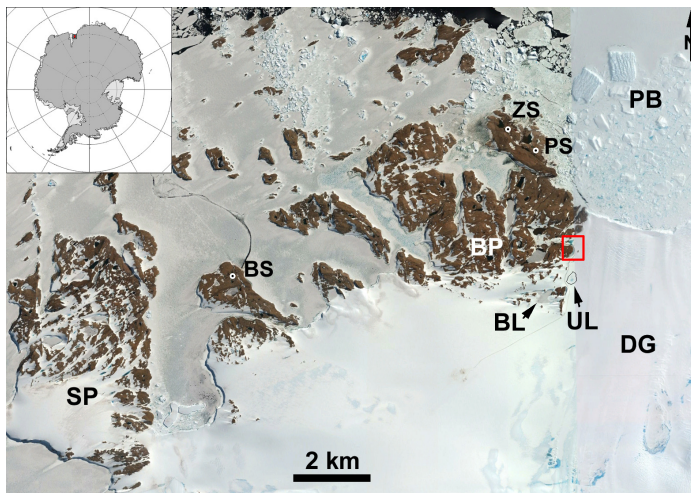


Figure 1. Geographical location of the Larsemann Hills (the Google Earth mosaic). BP — Broknæs Peninsula, SP — Stornes Peninsula, PS — Progress Station, ZS — Zhongshan Station, BS — Bharati Station, DG — Dålk Glacier, BL — Boulder Lake, UL — unnamed lake, PB — Prydz Bay; red frame — the area of the Dålk Glacier subsidence (see Fig. 3).

distance is 210 km; minimum and maximum flight altitudes are 100 m and 4000 m, correspondingly. Geoscan 201 consists of a composite fuselage and compound wings; takeoff preparation time is 10 minutes. On board there are: (1) A modem for the telemetry communication with a laptop ground control station (GCS); (2) A visible-band digital camera Sony DSC-RX1 equipped with a Carl Zeiss Vario Sonnar T lens (a central shutter; a 35 mm focal length) and a 35.8 mm × 23.9 mm sensor with a Bayer filter (a 6000 × 4000 matrix with a pixel size of 6 μm × 6 μm); and (3) A GNSS receiver Topcon utilized for high-precision determination of image projection centers. A ground GNSS base station includes a receiver Topcon HiPer V.

To consider the lens distortion, we previously performed a laboratory photogrammetric calibration of the camera, as well as a field camera calibration [1]. The following camera settings are used during an aerial survey: (1) The lens is locked to focus to infinity; (2) The shutter speed priority are 1/1000 s and 1/800 s for sunny and cloudy weather, correspondingly; (3) An aperture and ISO sensitivity values are selected automatically, one time per a flight line; and (4) Images are recorded as JPEG files.

The Geoscan 201 flight is performed in an automatic mode using an autopilot. One should specify a flight mission in the GCS by selecting a surveyed area and setting flight parameters. The key parameter is an overlap between images. It is recommended to set 70 % and 50 % forward and side overlaps, correspondingly. Then, one of the three interrelated parameters should be set: ground sample distance, flight altitude, and flight strip width. Flights can be conducted either at a constant altitude



Figure 2. A UAS Geoscan 201 [6].

above ground level (AGL) or a constant altitude above sea level. We used the first option. Finally, a GCS program calculates the flight lines and coordinates of image capture positions.

Before sending the Geoscan 201 to Antarctica, it was modernized as follows: (1) A filament was built into the camera lens to evaporate the possible condensate when passing through 0° C; (2) A self-heating function was embedded in the rechargeable batteries; and (3) The rubber catapult was supplemented by a spring.

### B. Aerial Surveying

During the austral summer 2016/2017, an unmanned aerial survey of the Larsemann Hills and adjacent areas was conducted within the 62<sup>nd</sup> Russian Antarctic Expedition in cooperation with Geoscan Ltd [7]. The main goal of the aerial survey was updating of the local topographic map. The unexpected subsidence in the Dålk Glacier, coincided with this mission, occurred on January 30, 2017. A territory including the subsidence zone with an area of about 7.5 km<sup>2</sup> was surveyed in two flights, before and after the event, that is, on January 20 and February 9, 2017. The first flight was carried out as a part of the Larsemann Hills aerial survey, while the second flight was specially organized.

During both flights, the weather was sunny. The air temperature ranged from −1° C to −5° C; the wind was northeast; the wind speed was 0–5 m/s at the flight altitude (310–350 m AGL). The aerial surveying consisted of 20 and 30 flight strips including 1,594 and 1,011 images for the first and second flights, correspondingly. Each flight took about 2 hrs. For all flights, forward and side overlaps were about 70 % and 50 %, correspondingly. Aerial images (Fig. 3) have an average resolution of 6 cm.

### C. Image Processing

The image processing consisted of two main stages: (1) a post-processing of the on-board GNSS receiver measurements relative to the base station; and (2) a photogrammetric processing of the aerial surveying data. For the first stage, we used Pinnacle software (Topcon Positioning Systems, Inc.). For the second stage, we used Agisoft PhotoScan Professional 1.3.2 software [8]. We generated two DEMs with a resolution of 22 cm related

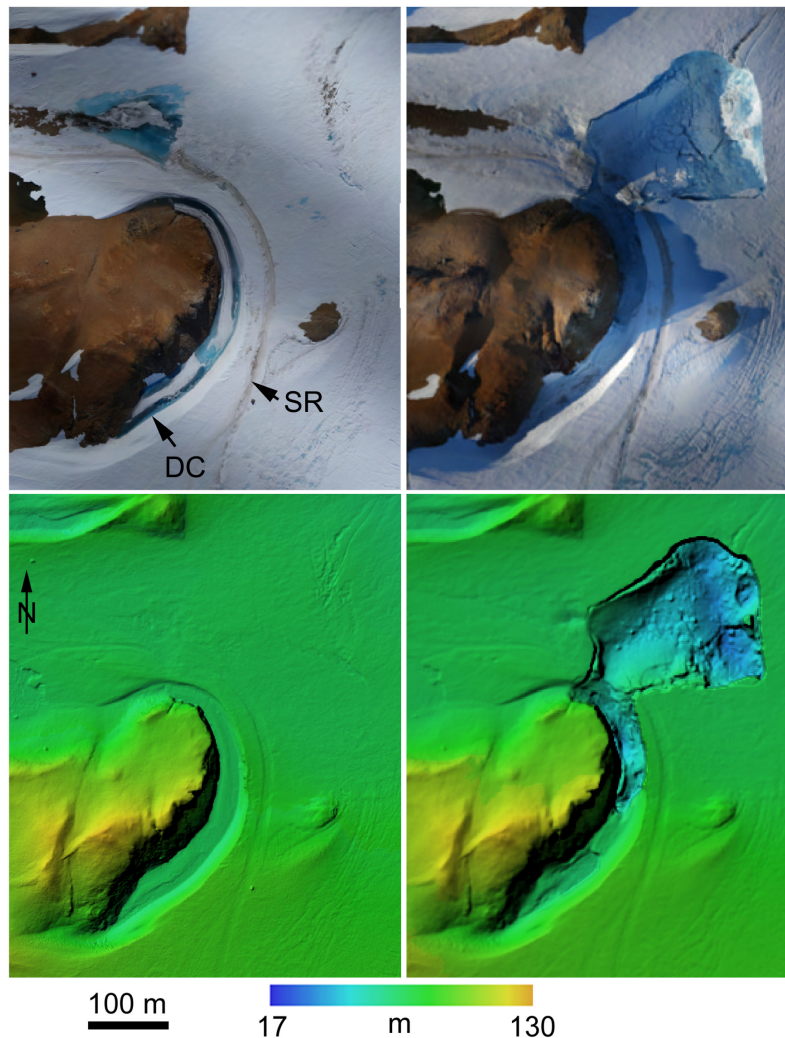


Figure 3. Orthomosaics (upper) and elevations (lower) of the north-western margin of the Dalk Glacier before (left) and after (right) the surface collapse (for the location, see Fig. 1). SR — a sledge route, DC — a drainage channel.

to the pre- and post-collapsed glacier surface (Fig. 3). The DEMs describe a mixed surface consisting of bedrock and ice. Finally, to model the pre-collapsed subglacial cavern, we subtracted one DEM from the other (Fig. 4). To superpose the models, we used 7 control points: stones on ice-free hills and corners of buildings at the field base Progress 1 on the hill nearest to the collapsed zone. Lateral ( $X$  and  $Y$ ) and vertical ( $Z$ ) mean errors and standard deviations of the superposition were as follows:  $X = 0.006 \pm 0.050$  m,  $Y = -0.020 \pm 0.058$  m, and  $Z = 0.056 \pm 0.141$  m.

#### IV. RESULTS AND DISCUSSION

Orthomosaics and DEMs clearly display results of the

catastrophic subsidence in the north-western margin of the Dalk Glacier (Fig. 3). According to these data, the depression measured 183 m by 220 m, and its area reached up to 40,000 m<sup>2</sup>. The maximum depth of the depression was 43 m. An approximate volume of the subglacial cavern was about 885,000 m<sup>3</sup> (Fig. 4). Note that these values were actual for February 2017 because of ice melting and movement.

We suppose that this subsidence may be a result of a *jökulhlaup*, a subglacial flood [9]. *Jökulhlaups* have already been discussed in relation to the Antarctic subglacial hydrosphere [10].

In the discussed case, the supposed chain of events is as follows [11]. A subglacial water flow originated within the

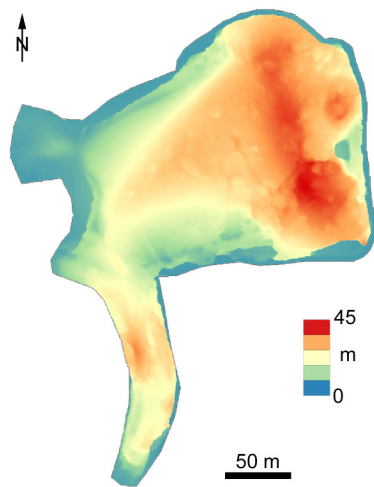


Figure 4. Thickness of the pre-collapsed subglacial cavern.

Boulder Lake basin located 1.5 km south of the subsidence zone (Fig. 1). The water gradually accumulated there due to the influx of melted glacier water. This accumulation could last several years. When the water level reached a certain critical point, a water breakthrough occurred because of the hydrostatic pressure and thermal expansion of water flow channels. The water breakthrough developed rapidly due to the excess of water temperature over melting ice temperature and the heat released by water flow movement. This led to the formation of a drainage channel.

Indeed, post-event aerial images show a channel flowing out from the Boulder Lake northwards. The channel connects the Boulder Lake with a bright blue area corresponding to an unnamed subglacial lake, which is located between the Boulder Lake and the subsidence zone (Fig. 1). Apparently, after the breakthrough of the Boulder Lake, water flowed into the unnamed lake via the intraglacial water drainage channels, filled it, and then burst through. Water flowed further northwards coming to the surface as a drainage channel adjacent to eastern and south-eastern slopes of an ice-free hill (Fig. 3). This process was promoted by numerous crevasses within the glacier body. We observed the rapidly flowing water at various sites between the hill and formed depression.

Then, water flowed under the Dalk Glacier via the existing and newly formed channels, combining them into a single, wide channel. One can see it as the southern elongated portion of the cavern model (Fig. 4). Probably, the subglacial cavern (Fig. 4) had already existed there. The water flow entered the cavern through this wide channel. Water eroded the cavern and gradually filled it. This process led to the water breakthrough from the cavern, emptying it via intraglacial channels going

towards the Prydz Bay, and, finally, as a result, the ice subsidence.

This hypothesis requires additional field studies to be carried out in the austral summer 2017/2018.

## V. CONCLUSIONS

The study shows the capabilities of UASs and UAS-based photogrammetry for rapid collection and generation of high precision and resolution images and DEMs in difficult-access and dangerous areas under severe conditions of polar regions.

The 2017 catastrophic subsidence in the Dalk Glacier is of great scientific interest in the context of studying subglacial reservoirs and under-ice hydrographic networks.

The subsidence destroyed a section of a route from the Progress Station to the local airfield and Vostok Station (Fig. 3). Several vehicles passed this section a few hours just before the event. So, the study of this event is also important for ensuring the safety of people in Antarctica.

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