NERC GEOPHYSICAL EQUIPMENT FACILITY SCIENTIFIC REPORT

Loan 838 and Loan 870: Geophysical exploration of a West Antarctic subglacial lake

Dr John Woodward[1], Dr Andy Smith[2], Professor Martin Siegert[3], Dr Neil Ross[3]

[1]*School of Applied Sciences, Northumbria University. Newcastle-upon-Tyne. NE1 8ST.*
T: 0191 2273048 E: john.woodward@northumbria.ac.uk
[2]*British Antarctic Survey, High Cross, Madingley Road, Cambridge. CB3 0ET.*
[3]*School of Geosciences, University of Edinburgh West Mains Road, Edinburgh. EH9 3JW.*

Abstract

NERC GPS units were deployed above Subglacial Lake Ellsworth during two austral summer field campaigns (2007/8 and 2008/9). During the first season four base stations were deployed. Two base station sites were reoccupied in the second field season. Base stations were used to monitor ice flow over SLE and to correct: i) stop-and-collect GPS data from a stake network positioned over and around SLE, ii) kinematic GPS data collected during radio-echo sounding profiles, and iii) stop-and-collect short occupancy records used to locate seismic shot hole positions. All activities requiring GPS positioning were successfully completed. Results from base stations and the stake survey show convergent ice flow over SLE, increasing ice flow along the lake length and greatest ice flow over the middle of the lake, decreasing towards the lateral margins. The GPS records were unable to detect a tidal cycle from the lake though may indicate gradual filling of the lake relative to the off-lake base station, though this could be an artefact of differential snow densification beneath the GPS units.

1 Background

Antarctic subglacial lakes are one of the few remaining unexplored environments on Earth. Found beneath both the East and West Antarctic ice sheets, these lakes are extreme environments thought to host unique microbiological life-forms that may have been isolated for millions of years. The sediments that have accumulated at the bottom of subglacial lakes may contain important records of Antarctic ice sheet history. Prior to the direct exploration, measurement and sampling of lake waters and underlying sediments, physical characterisation of target lakes and their topographic setting is necessary. Geophysical methods such as radio-echo sounding (RES) and seismic reflection are ideal tools for making these observations, providing data vital for constraining numerical modelling of the physical processes (melting, refreezing, water circulation) that can operate within subglacial lakes. These models can, in turn, guide the selection of target locations for access, sampling and measurement.

2 Subglacial Lake Ellsworth

Subglacial Lake Ellsworth (SLE) is a small subglacial lake (~12 km long by 3 km wide) in West Antarctica. The lake, which lies beneath 2.9-3.2 km of ice, is located within the catchment of the Pine Island Glacier in a deep subglacial trench ~30 km north of the central ice divide of the West Antarctic Ice Sheet, and some ~70 km west of the Ellsworth Mountains (Figure 1).

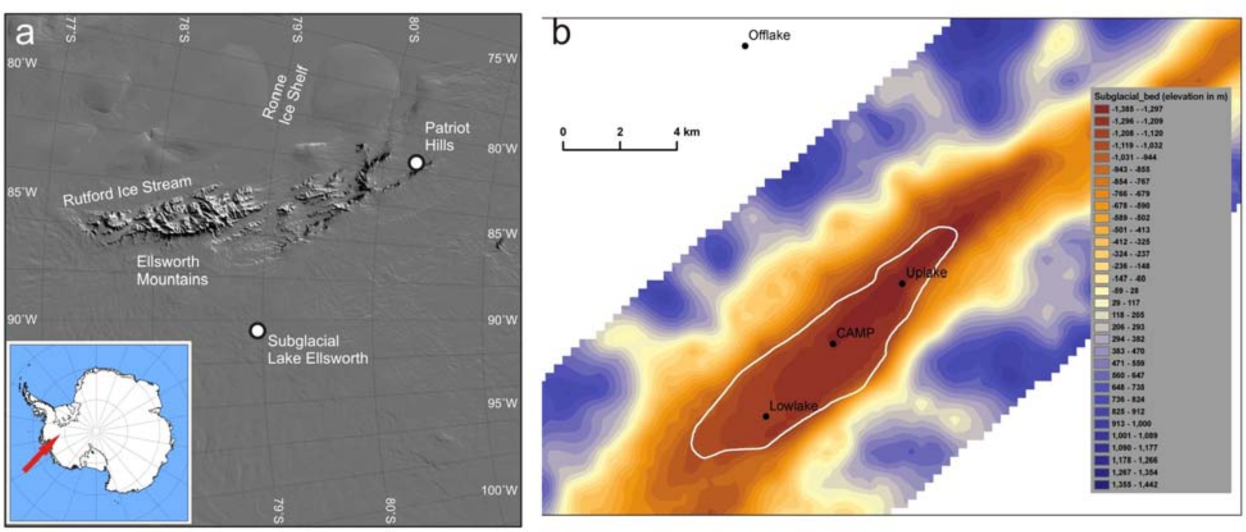

Figure 1: (a) Location of Subglacial Lake Ellsworth (SLE), West Antarctica. Background imagery is the MODIS mosaic of Antarctica (MOA) image map; (b) Outline of SLE and positions of GPS base stations in the 2007-08 season. 'Offlake' and 'Camp' were re-occupied in 2008-09. Base map is the subglacial bed derived from RES surveys.

3 Scientific aims

During the Austral summers of 2007-08 and 2008-09 a full geophysical characterisation of SLE was undertaken. The aims of this fieldwork were to:

1. Determine lake water depth and bathymetry (seismic reflection, located using GPS).
2. Map the outline of the lake and the topography of its catchment (RES, located using GPS).
3. Produce a detailed map of ice flow over the lake (GPS).
4. Characterise the nature of the ice-water and water-bed interfaces (seismics and RES).
5. Establish sediment thickness beneath the lake floor (seismic reflection, located using GPS).
6. Map the geometry of englacial layering within the overlying ice sheet (RES, located using GPS).
7. Measure any detectable tidal signatures (GPS).

4 GPS data acquisition

4.1 Field season 1 (2007-08)

Six Leica 530 Series GPS units were used at the SLE field site during the 2007-08 field season. Four units were used as static stations (with choke ring antennas) (Figure 1), with the primary role of monitoring any tidal signal in the lake, determining the ice sheet flow regime (velocity and direction) and to process all kinematic and stop-and-collect datasets (Appendix 1 records dates and details of surveys).

- *‘Offlake’ station* (continuous record, sampling rate of 5 secs): Situated on the ice surface, ~11 km from the centre of the lake. This station acted as a temporary base station for processing data from the other three static GPS stations.
- *‘Uplake’ station* (continuous record, sampling rate of 5 secs): Located at the up-ice end of the lake, within 1-2 km of the floatation point.
- *‘Camp’ station* (continuous record, sampling rate of 1 sec): Located at the field camp near the centre of the lake. This station acted as a temporary base station for processing kinematic and stop-and-collect datasets.
- *‘Lowlake’ station* (continuous record, sampling rate of 1 sec): Positioned at the down-ice end of the lake, within 1-2 km of the re-grounding line.

The two remaining GPS units were used as rover units to record the location of a network of stakes on the ice sheet surface (used to calculate flow velocities, direction and surface strain), in kinematic mode when collecting RES survey lines and in RTK mode to lay out seismic reflection lines.

4.2 Field season 2 (2008-09)

Three Leica 1230 Series GPS units were used at the SLE field site during the 2008-09 field season:

- *‘Camp’ station* (continuous record, sampling rate of 1 sec, choke ring antennas): Located at the field camp near the centre of the lake for the entirety of the field season, this unit acted as a base station for processing stop-and-collect and kinematic GPS data. The unit re-occupied the location (after ice movement) where data were acquired during the first field season.
- The two remaining GPS units were initially used to record the position and elevation of the network of stakes deployed on the ice sheet surface during the first field season.
- After acquisition of the stake network data, one GPS unit re-occupied the *‘Offlake’ station* (where GPS data were acquired during the 2007-08 field season). Data were recorded continuously at a 2 sec sampling interval using a choke ring antenna. The second remaining unit was used to record kinematic GPS data during the acquisition of RES data.

5 Data-specific acquisition parameters and post-processing methodology

5.1 Static data (base station data)

During the first field season static GPS data were acquired at a sampling rate of 5 secs (Offlake and Uplake stations) or 1 sec (Camp and Lowlake stations). The off-lake base station was processed by Dr Matt King (Newcastle University) using a kinematic Precise Point Positioning approach implemented in the GIPSY software. The remainder of the network was then processed relative to this post-processed ‘Offlake’ station. The kinematic Precise Point Positioning approach was required to overcome local site motion associated with ice flow and was deemed necessary because daily site motion could have been greater than 0.1 m. Initial processing of the data to evaluate the presence of a tidal signature was undertaken using the Track software (part of the GAMIT/GLOBK package).

5.2 Stop-and-collect data (stake network data)

The stake network consisted of 58 aluminium 'glaciopoles', installed on the snow surface over the lake during field season 2007-08 and 8 wooden stakes installed downstream of SLE by a team from the Centro de Estudios Científicos (CECS), Chile, in January 2006. GPS measurements of both glaciopoles and wooden stakes were made during both field seasons. Measurements of each of the stakes in the network were of a minimum duration of 20 minutes. The positions of both the poles and the stakes were corrected in post-processing (in Leica GeoOffice) using the 'static' camp base station (~78.98S 90.51W). Daily data files from the camp station were individually processed using the "Online Global GPS Processing Service (CSRS-PPP)" provided by Natural Resources Canada (NRC) (http://www.geod.nrcan.gc.ca/products-produits/ppp_e.php). The calculated position for each day was used as a control to process the stake network.

5.3 Kinematic data (for seismic reflection and RES data)

Five seismic reflection lines were acquired across the width of SLE. Data from these lines has been used to: i) map the lake bathymetry and ii) investigate the possible thickness of any sediment body beneath the lake. GPS equipment and data were used to site the locations of the seismic shot holes (in RTK mode) and to accurately record their positions and elevations. Post-processing of data followed the procedures set out for the stake network above (Section 5.2).

A detailed grid of radio-echo-sounding (RES) survey lines was acquired over the lake and its surroundings using the ground-based DELORES radar system (Figure 2). The RES survey was designed to define: i) the outline of Lake Ellsworth and its glaciological and topographic setting; ii) the geometry of internal layering within the overlying ice. GPS equipment was used in kinematic mode (sampling rate 1 second) to record the positions of the individual radar measurements (traces). Data were logged using both the GPS receiver and in the radar itself, by recording an NMEA string output generated by the receiver. The position of the GPS antenna was determined using kinematic solutions tied to the temporary local base station near the field camp ('Camp' GPS unit). This post-processing (of data from both field seasons) was undertaken using Leica GeoOffice with control from daily base station positions calculated using a precise point positioning processing methodology (see section 5.2).

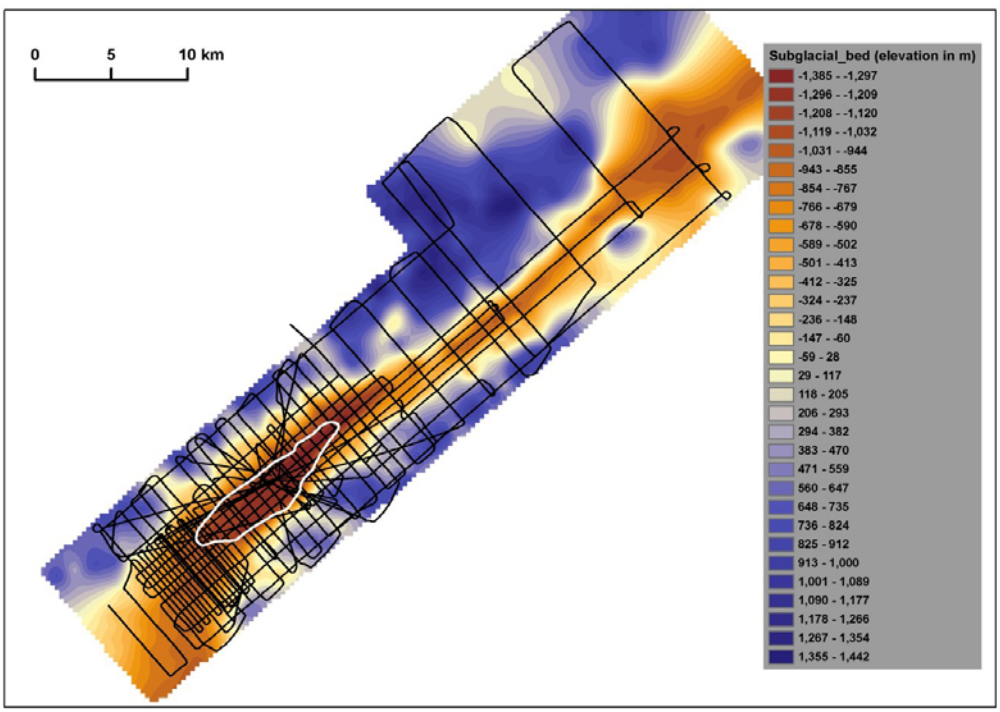

Figure 2: Map of kinematic GPS data acquired during RES surveys at Subglacial Lake Ellsworth. The black lines mark the acquisition of GPS data. RES data were not always acquired along the survey lines shown (e.g. in transit to and from the start of RES survey lines). Lake outline is shown as a white polygon. Base map is revised subglacial topography from RES surveys.

6 Results

6.1 Static (base station data for lake-surface change)

Movement of the three 'on-lake' GPS stations were computed relative to the OFFLAKE site data. These results show that the ice surface over the lake was apparently increasing in elevation over the observation period (field season 2007-08). A downlake trend was also observed, with the rate of elevation change increasing from the uplake to the lowlake stations. This is demonstrated in Figure 3, which shows a rise in the vertical elevation of each of the three on-lake stations during the 2007-08 field season, with the most pronounced vertical change being at the lowlake station. A short, but pronounced, increase in elevation (relative to the background increase) is apparent in all static base station records between days 350 and 360 (year 2007). This gradual rise may indicate very slow filling of the subglacial lake, but could also be explained as a result of differential settling of the snow surface from the off-lake to on-lake sites. Analysis of the base station datasets indicates that no tidal signature was apparent.

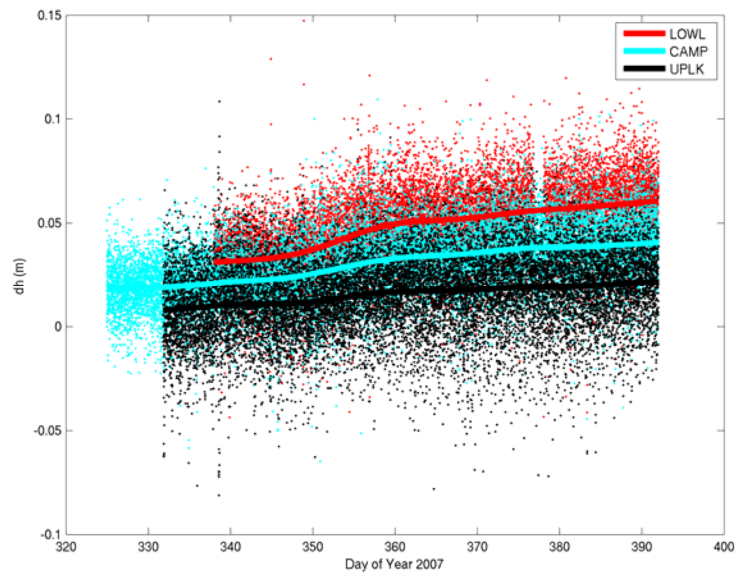

Figure 3: Vertical elevation change of the 'onlake' base stations (Lowlake, Camp and Uplake) during the 2007-08 field season period of observation. All data computed relative to the Offlake base station.

'On-lake' station	'Control' station	Vertical change (m a^{-1})	Uncertainty (m a^{-1})
LOWL	OFFL	+0.2267	0.0031
CAMP	OFFL	+0.1464	0.0020
UPLK	OFFL	+0.0877	0.0030

Table 1: Vertical elevation change of temporary 'onlake' base stations computed relative to the Offlake station (2007-08 fieldseason).

The direction and annual rate of ice flow were also computed from the base station datasets. These data indicate: (a) an extensional flow regime along the length of the lake; (b) convergent flow between the Camp and Offlake stations; and (c) a westward trending curvature to flow downlake (from uplake to lowlake). The observed extensional flow regime over the lake is of particular interest as such a regime would normally be associated with a negative vertical strain rate, the opposite of that observed in the data (Tables 1, 2 and Figure 3).

Station	Flow rate (m a^{-1})	Uncertainty (m a^{-1})	Flow direction (degrees)	Uncertainty (degrees)
OFFL	1.9	+- 0.1	298.2	+- 2.0
UPLK	4.5	+- 0.2	318.9	+- 2.3
CAMP	4.9	+- 0.1	313.3	+- 0.9
LOWL	5.5	+- 0.1	310.8	+- 0.8

Table 2: Ice sheet flow velocity and direction measured at the four temporary base stations deployed above and near SLE during the 2007-08 field season.

6.2 Static ('stop-and-collect' - stake network for ice flow)

From the measured changes in the positions of the stakes in the stake network between the 2007-08 and 2008-09 field seasons the direction and rate of ice flow at the ice surface were calculated. This has been used to produce a detailed map of the rate and direction of ice flow over the lake (Figure 4). The data will be used to calibrate numerical models of ice sheet flow and to compare the present ice flow regime with past records of flow derived from englacial layering in RES data.

GPS measurement of the stake network shows that ice flow over Subglacial Lake Ellsworth is characterised by three overall trends.

(1) Convergent ice flow over the lake: A westward rotation of the orientation of flow occurs across the lake from 'Ellsworths distal' to 'Ellsworths proximal'. Measurements made across the middle of SLE demonstrate this trend. Ice flow at the 'easternmost' datapoint (Ellsworths 'proximal') is orientated at ~310º, whilst 'west' of the lake (Ellsworths 'distal') ice flow is orientated at ~319º. A progressive decreasing trend is observed between these two points, with ice flow above the centre of the lake trending at ~314º. The degree of convergence is greatest at the top end of the SLE, with a noticeable decrease in convergence apparent down-lake.

(2) *Increasing ice flow velocity down the length of the lake*: The measured rate of flow increases from ~3.7 ma-1 near the head of SLE, to ~6 ma^{-1} around the lake outlet. Over the midpoint of the lake measured ice flow is 4.95 ma^{-1}. The maximum flow velocity measured was ~6.6 ma^{-1}, at a datapoint some 4.5 km downstream of SLE.

(3) *Ice flow velocity is greatest over the middle of the lake, decreasing towards both its lateral margins*: Velocities of ~4.64 ma^{-1} have been measured ~1-1.2 km beyond the lateral lake margins, compared to the flow rate of 4.95 ma^{-1} above the midpoint of the lake. Rates of flow decrease progressively from the lake centre towards each of the lateral datapoints.

These three overall trends are independently verified by the observations made using the four static base stations during the 2007-08 field season.

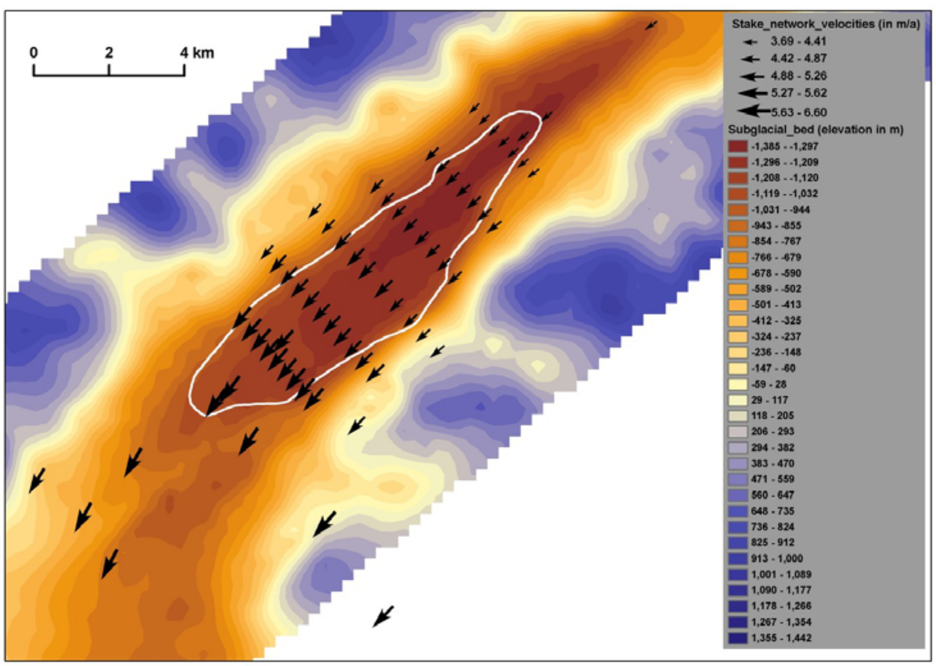

Figure 4: Detailed map of ice flow velocity and orientation over Subglacial Lake Ellsworth derived from GPS observations of temporary stake network in field seasons 2007-08 and 2008-09. Size of arrows provide an indication of the rate of flow. Base map is revised subglacial topography from RES surveys.

7 Presentations at international conferences

Ross, N., Smith, A.M., Woodward, J., Siegert, M.J., Hindmarsh, R.C.A., Corr, H.F.J., King, E.C., Vaughan, D.G., (2008). Radio-echo sounding exploration of Subglacial Lake Ellsworth, West Antarctica. International Symposium on Radioglaciology and it's Applications, Madrid, June 2008.

Smith, A.M., Woodward, J., Ross, N., Siegert, M.J., Corr, H.F.J., Hindmarsh, R.C.A., King, E.C., Vaughan, D.G. and King, M.A., (2008), Physical conditions in Subglacial Lake Ellsworth, Forum for Research in Ice Shelf Processes (FRISP), Annual Workshop, Derbyshire, September 2008.

Smith, A.M., Woodward, J., Ross, N., Siegert, M.J., Corr, H.F.J., Hindmarsh, R.C.A., King, E.C., Vaughan, D.G. and King, M.A., (2008), Physical conditions in Subglacial Lake Ellsworth, EOS, Transactions, AGU, 89(53), Fall Meet. Suppl.: Abstract C11A-0467.

Ross, N., Smith, A.M., Woodward, J., Siegert, M.J., Corr, H.F.J., King, E.C., Hindmarsh, R.C.A., and Vaughan, D.G., (2009). Geophysical characterisation of Subglacial Lake Ellsworth, West Antarctica. Geophysical Research Abstracts, Vol. 11, EGU2009-1088.

Woodward, J., Smith, A.M., Ross, N., Thoma, M., Siegert, M.J., Corr, H.F.J., King, E.C., Vaughan, D.G., and King, M., (2009). Bathymetry and basal mass balance of Subglacial Lake Ellsworth, West Antarctica. International Symposium on Glaciology in the International Polar Year 2009, Newcastle upon Tyne, July 2009.

Ross, N., Smith, A.M., Woodward, J., Siegert, M.J., Corr, H.F.J., Hindmarsh, R.C.A., King, E.C., Vaughan, D.G., (2009). Ice flow and catchment morphology of Subglacial Lake Ellsworth as revealed by ice-penetrating radar. International Symposium on Glaciology in the International Polar Year 2009, Newcastle upon Tyne, July 2009.

8 Appendix: Data collection and field dates

Directory	Sub-directory	2nd SD	Contents
SLE_GPS	Offlake	28_11_07	Continuous 5s data set for permanent station on ice above a bedrock high.
		27_01_08	
	Uplake	27_11_07	Continuous 5s data set for permanent on-lake station
		31_12_07	
		27_01_08	
	Camp	20_11_07	Continuous 1s data set for permanent on-lake station
		01_12_07	
		10_01_08	
		31_01_08	
	Lowlake	22_12_07	Continuous 1s data set for permanent on-lake station
		12_01_08	
		27_01_08	
	Survey	27_11_07	A series of point measurements with 1s collection for up to 20 minutes Points are in survey lines
		28_11_07	
		28_11_07b	
		29_11_07	
		29_11_07b	
		30_11_07	
		01_12_08	
	Resurvey	27_01_08	Resurvey of points with 5 minute occupation. Some longer points (20 mins) A re first survey of new poles.
		29_01_08	
		31_01_08	
	Coffee can		Single static survey 1s for ~20 hours
	Lake1_ses		A series of points with 1s collection For approx. 5 minutes per stake
	Lake2_ses		
	Lake3_ses		
	Lake4_5_ses		
	DELORES 0708		Intermittent kinematic data acquired between 31/12/07 to 27/01/08
	Camp	*29/12/08*	Continuous 1s data for permanent on-lake station
		28/01/09	
	Offlake	*13/01/09*	Continuous 2s data for off-lake station
		24/01/09	
	Survey		58 poles + 8 stakes (@ >20 min measurement periods), measured over 5 days (*30/12/08, 31/12/08, 01/01/09, 02/01/09, 06/01/09*).
	Coffee_can	*28/01/09*	one 20 hour measurement period
	DELORES 0809		Intermittent kinematic data acquired between 10/01/09 to 27/01/09