Supplementary material for

The Aneto Glacier (Central Pyrenees) evolution from 1981 to 2022: ice loss observed from historic aerial image photogrammetry and recent remote sensing techniques

Ixeia Vidaller[1], Eñaut Izagirre[2], Luis Mariano del Rio[3], Esteban Alonso-González[1], Francisco Rojas-Heredia[1], Enrique Serrano[4], Ana Moreno[1], Juan Ignacio López-Moreno[1], Jesús Revuelto[1]

[1] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC), Zaragoza, Spain

[2] Department of Geography, Prehistory and Archaeology, University of the Basque Country UPV/EHU, Vitoria-Gasteiz, Spain

[3] Department of Applied Physics, Escuela Politécnica Superior de Cáceres, University of Extremadura, Cáceres, Spain

[4] Department of Geography, GIR PANGEA, University of Valladolid, Valladolid, Spain

Corresponding author: Ixeia Vidaller (ixeia@ipe.csic.es)

2.2 In situ Ground Penetrating Radar (GPR), processing and data interpolation

A total of 32 georeferenced radargrams were recorded in a common offset mode, corresponding to a length of 6.8 km and covering almost the entire glacier surface (Figure S1 and Table S1). To determine the distance recorded in each transect, a GPS was connected to the GPR to obtain the data in "time" tuning: the instrument was configured to transmit pulses at constant time intervals. A wheel odometer connected to the device was used for the shielded antenna. In addition, an external wheel odometer was used to estimate, on the one hand, the distance travelled by the RTA obtained by georeferencing and, on the other hand, compare it to the internal wheel odometers of the shielded antennas. The lengths of the radargrams were measured in different ways. The lengths estimated from the coordinates received with the GPS coupled to the instrument and processed by the ReflexW software were found to correspond most closely to the actual length of the transects performed.

2.4 Correction and accuracy assessment

The values obtained with the external odometer are significantly different (Table S1) from the other two because the displacement on the surface of the external wheel is not uniform (it can slide without moving) and the surface itself is not flat but has grooves and undulations. On the other hand, the distance estimated by Google Earth, although similar to that determined with ReflexW from the coordinates obtained with decoupled GPS, is subject to errors due to the manual marking of the beginning and end of the radargram in the map.

Table S1: Main characteristics of antenna frequency, orientation and direction: downward (S–N) or upward (N–S) and E–W or W–E.

Radargram	Antenna (MHz)	Orientation	Longitude (m) (ReflexW coordinates)	Longitude (m) (Google Earth)	Longitude (m) (external odometer)
1037	RTA 100	S–N	336	306	320
1038	RTA 100	N–S	272	354	230
1041	RTA 100	N–S	151		134
1042	RTA 100	E–W	153	143	138
1043	RTA 100	S–N	293	281	278
1044	RTA 100	W–E	197	194	173
1045	RTA 100	N–S	48	38	33
1046	RTA 100	W–E	284	271	387
1047	RTA 100	E–W	56	211	47
1052	RTA 100	E–W	161	–	137
1054 (*)	AP 100	S–N	338	283	279 (*)
1059	RTA 100	E–W	294	266	182
1060	RTA 100	W–E	116	112	74
1061	RTA 100	N–S	49	38	38
1062	RTA 100	E–W	1003	997	838
1063	RTA 100	W–E	242	244	220
1067	RTA 100	W–E	625	607	544
1068	RTA 100	S–N	166	176	159
1069	RTA 100	E–W	699	703	595
1070 (*)	AP 500	E–W	34	32	21 (*)
1071 (*)	AP 500	N–S	30	30	25 (*)
1073	RTA 100	N–S	287	249	250
1074	RTA 100	S–N	379	378	363
1075	RTA 100	N–S	36	45	35
1078	RTA 100	N–S	287	250	255
1079	RTA 100	S–N	116	111	129
1090	RTA 100	S–N	281	279	262
1091	RTA 100	W–E	27	34	25
1093	RTA 100	W–E	171	168	154
1094	RTA 100	E–W	168	166	149
1096	RTA 100	E–W	290	294	235

(*) Shielded antenna, distance measured with internal odometer.

To check the coherence of the thicknesses obtained, a test was carried out at all the intersections between the transects to detect any inconsistencies in the values. These inconsistencies may be due mainly to the fact that in some sections of the radargrams it is difficult to determine exactly the interface between the ice and the rocky bottom.

Table S2: Intersection points, radargrams implied in the intersection point, and the thickness difference obtained. As can be seen, radargram 1037 was excluded, because the obtained transect is almost identical to the shielded 100 MHz antenna with higher resolution (1054).

Intersections radargrams	Intersection coordinates	Thickness difference (m)
1041/1042	307611.4; 4722878.4	1.7
1042/1054	307561.8; 4722927.2	0.8
1042/1043	307541.8; 4722941.3	3.4
1041/1052	307635.7; 4722957.3	0.3
1052/1054	307588.3; 4722963.7	2
1052/1043	307563.3; 4722979.6	0.3
1043/1046	307563.3; 4722979.6	0.7
1038/1044	307669.4; 4723132.5	0.6
1044/1045	307669.5; 4723132.5	0.5
1043/1044	307640.9; 4723143.4	0
1046/1059	307487.7; 4723195.1	1
1067/1068	307170.2; 4723329.2	2.1
1062/1068	307207.3; 4723380.7	0.3
1062/1079	306973.9; 4723354.8	2.2
1062/1078	306884.9; 4723587.8	2.6
1062/1067	306743.1; 4723643.9	5.3
1062/1074	306743.1; 4723643.9	0.3
1067/1074	306743.1; 4723643.9	5.6
1062/1073	306649.1; 4723697.2	1.2
1062/1063	306518.1; 4723782.6	3.9
1069/1073	306709.9; 4723772.2	1.4
1069/1074	306796.6; 4723710.5	2.1
1074/1096	306903.7; 4723834.5	0
1069/1078	306905.2; 4723641.4	0.3
1078/1096	306971.9; 472378.01	3.3
1069/1079	306995.3; 4723581.4	1.4
1090/1094	307081.8; 4723697.5	0.2
1093/1096	307151.9; 4723775.1	0.1

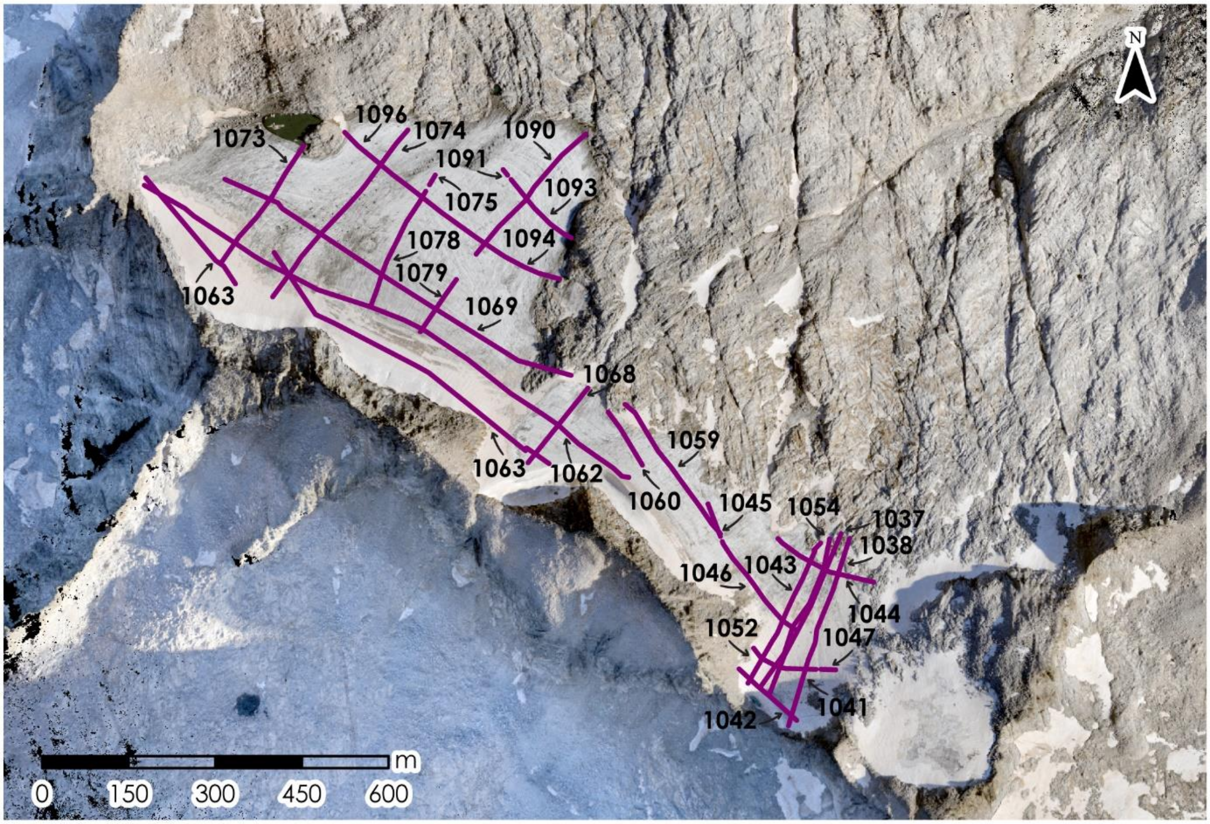

Figure S1: Purple lines indicate radargram transects with their ID number (see the characteristics of each radargram in Table S1).

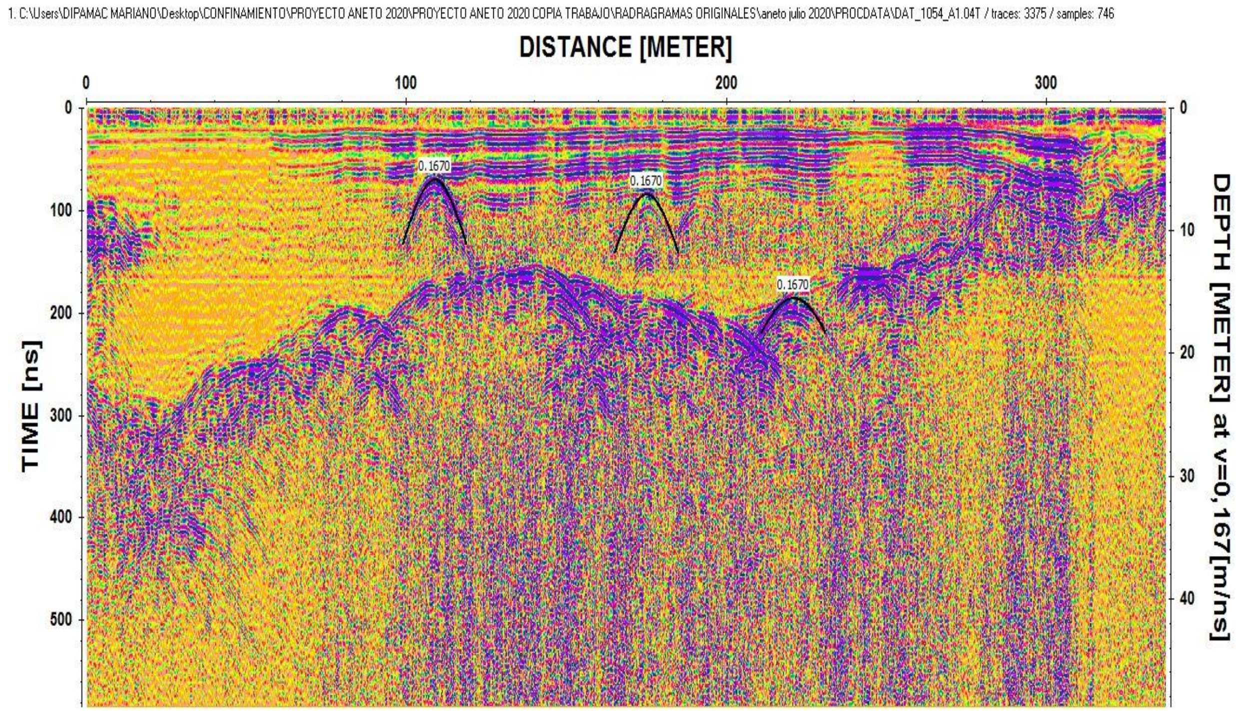

Figure S2: Radargram with the speed obtained in each diffraction hyperbole, considering the established RWV of snow and ice (0,200 and 0,163 m/ns respectively).