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A high-precision Jacob's staff with improved spatial accuracy and laser sighting capability

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4

5 **Abstract**

6 A new Jacob's staff design incorporating a 3D positioning stage and a laser sighting stage is
7 described. The first combines a compass and a circular spirit level on a movable bracket and the
8 second introduces a laser able to slide vertically and rotate on a plane parallel to bedding. The new
9 design allows greater precision in stratigraphic thickness measurement while restricting the cost and
10 maintaining speed of measurement to levels similar to those of a traditional Jacob's staff. Greater
11 precision is achieved as a result of: a) improved 3D positioning of the rod through the use of the
12 integrated compass and spirit level holder; b) more accurate sighting of geological surfaces by
13 tracing with height adjustable rotatable laser; c) reduced error when shifting the trace of the log
14 laterally (i.e. away from the dip direction) within the trace of the laser plane, and d) improved
15 measurement of bedding dip and direction necessary to orientate the Jacob's staff, using the
16 rotatable laser. The new laser holder design can also be used to verify parallelism of a geological
17 surface with structural dip by creating a visual planar datum in the field and thus allowing
18 determination of surfaces which cut the bedding at an angle (e.g., clinoforms, levees, erosion
19 surfaces, amalgamation surfaces, etc.). Stratigraphic thickness measurements and estimates of
20 measurement uncertainty are valuable to many applications of sedimentology and stratigraphy at
21 different scales (e.g., bed statistics, reconstruction of palaeotopographies, depositional processes at
22 bed scale, architectural element analysis), especially when a quantitative approach is applied to the

23 analysis of the data; the ability to collect larger data sets with improved precision will increase the
24 quality of such studies.

25 Keywords: Jacob's staff; Stratigraphic thickness; Sedimentary logging; Outcrop; Measuring errors.

26 **1. Introduction**

27 Measuring stratigraphic thicknesses in an accurate manner is one of the key data acquisition
28 workflows for sedimentologists and stratigraphers. Some examples of the type of research that
29 benefits from high precision stratigraphic thicknesses measurements include: characterisation of
30 depositional processes at bed scale (e.g., Eggenhuisen et al. 2011; Sumner et al., 2012; Fonnesu et
31 al., 2015); reconstruction of short-time variability of creation and fill of accommodation space (e.g.,
32 Banham and Mountney, 2003); architectural analysis (e.g., palaeo-depths of channels related to
33 measurements of channels fills and bars, Bridge and Tye 2000; deep water lobe thicknesses, Prélat
34 and Hodgson, 2013; Marini et al. 2015); outcrop-derived angles of progradation or aggradation of
35 parasequences (e.g., Zhu et al 2012); analysis of bed thickness statistics (e.g., Marini et al., 2016);
36 population of numerical models using thickness data from outcrop (e.g., Amy et al., 2013).

37 The simplest tool used in the field to measure stratigraphic thicknesses is a tape measure, commonly
38 the rigid folding type. This is quite effective in certain outcrop conditions, such as when measuring
39 horizontal beds on a vertical outcrop face or dipping beds on a face parallel to their dip direction
40 (e.g., along a road cut), because the apparent and real thicknesses of the beds in these
41 configurations coincide. However, when the apparent and real thicknesses of beds diverge,
42 measurement using a tape can be very difficult to carry out in a precise manner. For example, this is
43 the case with low relief outcrops where bedding is anything but vertical, such as while logging along
44 a ridge crest leading to a hilltop or along a wave-cut platform (Figure 1). Another situation when a
45 tape measure is not very effective is the case of a significant interval (e.g., metres to tens of meters)
46 without clear surfaces indicating the structural dip (e.g., a very thick unit without internal bedding or

47 with disrupted bedding or a covered interval). In these scenarios stratigraphic thickness
48 measurements must be carried out by sighting, for which the most effective tool is a Jacob's staff
49 (see Merriam and Youngquist (2002) for an historical prospective and for a discussion on the origin
50 of the name). In its simplest version a Jacob's staff for logging purpose is a vertical rod of known
51 height with a device to help sighting mounted on its top (e.g., a sight or a flat disc). The rod is then
52 placed orthogonal to bedding (often with the aid of a compass and a clinometer) and the sighting
53 device is used to measure true stratigraphic thicknesses (Figure 1; see also Compton (1985), chapter
54 11, and references therein). In the last twenty years, improved models of Jacob's staff have been
55 developed (e.g., Elder, 1989; Brand, 1995; Evans, 2002), aiming to increase measurement precision
56 and ease of use, while at the same time maintaining reasonable manufacturing costs. This paper
57 describes a new Jacob's staff, with some key improvements over the currently used models.

58 **2. New Jacob's staff**

59 *2.1. Design*

60 The new Jacob's staff (Figure 2A) consists of three main parts: a vertical rod measuring 210 cm, a 3D
61 positioning stage (Figure 2B-C) and a laser sighting stage (Figure 2D). The vertical rod is composed of
62 four pieces which can be connected and disconnected in the field for ease of carrying. Three of the
63 pieces are 50 cm long, and the uppermost is 60 cm long (see Figure 2E for a detail of the connecting
64 mechanism between rod pieces) combining to allow measurements up to 2 metres. The rod has a
65 cm-scale graduation from 0 to 210 cm, with each 10s of centimetre mark highlighted to make
66 reading vertical values easy. A first novelty of this new design is the 3D positioning stage (Fig. 2B-C).
67 This consists of a base plate compass and a circular spirit level glued on to a plate, which is
68 connected to an adjustable angle gauge by a 90 degree bracket. The bracket is mounted on a
69 vertically sliding block that can be fixed in a defined position using a screw clamp. With the angle
70 gauge set at zero, the plate on which compass and spirit level are hosted is orthogonal to the vertical
71 rod, but can be rotated in the vertical plane using the angular scale to match the structural dip of

72 bedding before being clamped in position. The second element of the novel Jacob's staff is a laser
73 sighting stage (Fig. 2D), which allows a pen-shaped laser to rotate around and to move up and down
74 along the rod. Note that the laser is only able to rotate on a plane orthogonal to the rod itself.

75 The materials were selected for their strength, weight, durability to wear and tear and for their lack
76 of magnetism, to avoid the compass being affected (aluminium being chosen for most of the parts,
77 including the rod). The rod parts and the angle gauge can be bought from most builders merchants,
78 while the laser holder was manufactured. Regarding the compass, a relatively inexpensive base plate
79 compass was deemed sufficient. For the laser, a very inexpensive green light 1mW laser was chosen
80 to allow its light to be visible even in bright sun and to a reasonable distance. The maximum sighting
81 distance is dependent on lighting conditions, and can vary from around 10-20 metres under direct
82 sunlight on a bright sunny day to >100 metres in dark cloudy conditions. Manufacturing and
83 assembly was carried out by Antony Windross and Stephen Burgess at the instrument workshop of
84 the School of Earth & Environment (University of Leeds).

85 *2.2. Suggested mode of use*

86 Before starting logging, as with any Jacob's staff, a precise measure of the strike and dip of the
87 bedding should be obtained. The four parts composing the rod should be assembled and the two
88 moving pieces (3D positioning stage and laser holder) inserted and fixed to the rod. The compass dial
89 should be set to the structural dip direction and the angle gauge should be set to the angle of dip.

90 To begin the measurement, the user should place the base of the rod on the initial point of
91 measurement (e.g., the base of a bed; a trowel inserted in the soil below the bed might be used to
92 provide a solid base in case of loose sediments). The Jacob's staff should then be aligned to be
93 orthogonal to structural dip checking that the North needle of the compass aligns with the North on
94 the compass dial and that the air bubble of the circular spirit level is in its central position (Figure 3).
95 At this point the user should start moving the laser holder vertically along the rod intermittently

96 activating the laser beam to check where the laser projects on the outcrop. Once a surface to be
97 recorded on the log (e.g., an internal surface within a bed, a base or a top of a bed, etc.) is
98 illuminated by the laser dot, a measure can be read off the graduated values on the rod. If in the first
99 2 metres there is not any significant surface, the position of the 2 m point (or another suitable value,
100 chosen to make the measurement easier) should be used as the starting point for the next
101 measurement. It should be noted that if the surfaces to be measured are very closely spaced (e.g., a
102 few centimetres in true vertical distance), it might be more time efficient to only use the Jacob's
103 staff to measure key surfaces spaced around 1-2 metres in true vertical distance and use a
104 conventional tape measure to integrate the measure by adding the intervening surfaces. By applying
105 this technique, the speed of measurement using the new Jacob's staff is roughly comparable to that
106 of a conventional staff.

107 *2.3. Main use of the rotatable laser*

108 Ideally, it would be best for the trace of the log to follow the direction of the structural dip of the
109 succession. However, this is not always possible and in some cases, a lateral shift is required. When
110 possible, this should be performed by walking a known surface parallel to bedding and restarting the
111 log in the new location. However, when this is not possible, accurate sighting may be necessary to
112 find a new starting point. A key design feature of the described Jacob's staff improves this action by
113 allowing the rotatable laser to describe a plane orthogonal to the Jacob's staff rod (i.e. on a bedding
114 plane). The user is therefore able to project the laser dot on the outcrop at any angle away from the
115 dip direction of the bedding (Figure 3). However, care must be taken as the larger the angle away
116 from the direction of the dip the more any error in the measured value of the strike direction and
117 dip angle used to orientate the Jacob's staff will be amplified. This effect is in addition to the error
118 caused by the longer sighting distance associated with this action. If the outcrop is mainly oriented
119 parallel to the bedding strike, any error on the strike value will be significantly amplified – errors on
120 the dip angle less so – and vice versa, so that on an outcrop mainly extending along the dip direction

121 errors in dip angle will be the most amplified. This type of error can be minimised by improving the
122 measurement of the direction and angle of the dip by using the rotatable laser (see next paragraph).

123 *2.4. Other uses of the rotatable laser*

124 If the outcrop is laterally extensive, rotating the laser holder will result in the laser dot projected on
125 the outcrop to 'follow' a surface parallel to the regional dip (e.g., the planar base of a thin sediment
126 bed). This technique can be used to verify and refine the value of strike and dip angle of the bedding
127 measured with a conventional compass. If it is clear from other sedimentological observations that
128 the surface in observation should be parallel to the regional dip and the laser dot on the outcrop
129 does not 'follow' it, it is likely that the values of dip direction and angle chosen to orientate the
130 Jacob's staff are not correct. Conversely, if the values of dip direction and angle are known to be
131 correct and the laser dot on the outcrop does not 'follow' a certain surface, it is possible to infer that
132 the surface in question is not parallel to structural dip. For example, this technique could help
133 recognise shallow clinoforms, levees, bar forms or remobilised deposits. In a sequence of
134 amalgamated event beds, it could make possible to establish if the amalgamation surfaces are
135 bedding-parallel or are at an angle to it, indicating incision. Similarly, in a section characterised by
136 low angle unconformities, this approach might improve their recognition and help establish the
137 degree of change in bedding attitude.

138 **3. Measuring errors**

139 Whichever technique is used, evaluating errors affecting stratigraphic measurements is difficult,
140 mainly because of the lack of a 'true' value against which to validate the results (in a tabular
141 succession, core from a behind outcrop drilling project could provide such 'true' value). In addition
142 to the skill of the user, key factors defining the amount of error are the type of instrument used for
143 logging (e.g., tape measure or different models of Jacob's staff) and the type of exposure. The latter
144 component can be broken down into the geometrical configuration of the topography in relation to

145 the regional structural dip (hence the required sighting distance; see Figure 1) and into the quality of
146 exposure (e.g., presence of soil or plant cover, intensive rock weathering, etc.).

147 The amount of error associated with measurements of stratigraphic thicknesses can be highlighted
148 by comparing logs of the same stratigraphic section by different authors. An example is provided by
149 the work of Kneller and McCaffrey (1999) and Patacci et al. (2014) who logged the same section
150 outcropping along the road D110 to the village of Braux, in the French Alps (Annot Sandstones).
151 Comparison of the 46m thick interval between the base of beds Z and A of Patacci et al., 2014
152 reveals that measurements of 24 1-3 metres thick intervals (from bed base to bed base) with rare
153 exceptions have differences of up to 10%. However, the differences tend to compensate each other
154 and differences for stretches of several meters are between 1% and 3%; both sections have excellent
155 outcropping conditions along the road cut and were logged with a tape measure.

156 The lack of a 'true' reference value when measuring stratigraphic thicknesses means it is difficult to
157 assess the precision of the newly designed Jacob's staff. However, Marini et al., (2016) recently
158 published the first dataset acquired with the new Jacob's staff described in this paper, a portion of
159 which can be compared with Log VI of Southern et al. (2015), logged with a traditional Jacob's staff.
160 Although the purpose of the work was different, both logs were measured at the same resolution
161 down to 1 cm. The logged section includes a mix of different logging conditions along a mountain
162 crest, with some very difficult stretches, both because of the geometrical configuration (e.g.,
163 bedding shallowly dipping into the subsurface and shallowly sloping terrain) and also because of
164 some covered or poorly outcropping intervals, making the use of the Jacob's staff essential.

165 Comparison of 19 selected 1-5 metres long intervals for which original measurement data were
166 available (for a total thickness of 48 metres) indicates differences up to 20%. As in the Braux road
167 section example, the differences tend to compensate, resulting in errors for stretches of several
168 meters between 2% and 5%. It should be noted that the larger differences in this case are likely due
169 to the difficult outcrop conditions and that a major benefit of the new Jacob's staff is thought to be

170 in reducing the larger errors associated with this type of scenario therefore improving measurement
171 repeatability.

172 Although the examples provided above (chosen principally on the basis of the data availability to the
173 author) might help the interpretation of stratigraphic thickness measurements and their associated
174 errors, a detailed comparison of different logging techniques and the resolution and repeatability of
175 such measurements is outside the scope of this paper; it is an area of methodological research
176 awaiting further study.

177 **4. Conclusions**

178 The described new Jacob's staff design includes a number of improvements which can be achieved
179 at a reasonable cost and are aimed at increasing the precision of stratigraphic thicknesses
180 measurement while maintaining the logging speed of a traditional Jacob's staff.

181 A number of factors contribute to an increase in measurement precision and repeatability compared
182 to a traditional Jacob's staff: a) improved 3D positioning of the rod through a revised compass and
183 spirit level holder; b) more precise sighting of measurement points due to movable laser stage; c)
184 reduced error when shifting the trace of the log laterally (i.e., away from the dip direction) and d)
185 improved measurement of bedding necessary to orientate the Jacob's staff. The last two factors are
186 possible due to the ability to turn the laser and project a visual planar datum to aid in the
187 recognition of depositional or erosional surfaces at an angle to structural dip.

188 Although defining the precision of the new instrument is challenging and awaits further work, a
189 short compilation of examples shows that stratigraphic thickness measurement errors can be
190 significant, especially when values for individual metres-long stretches are required. It is also
191 apparent that the largest errors occur most likely when outcrop conditions are difficult, in terms of
192 orientation of the geological structure to the land surface, or the degree of outcrop. In these
193 scenarios the new Jacob's staff can help to improve precision and repeatability of stratigraphic

194 thickness measurements and hence to reduce the associated uncertainty in the description and
195 interpretation of the dataset.

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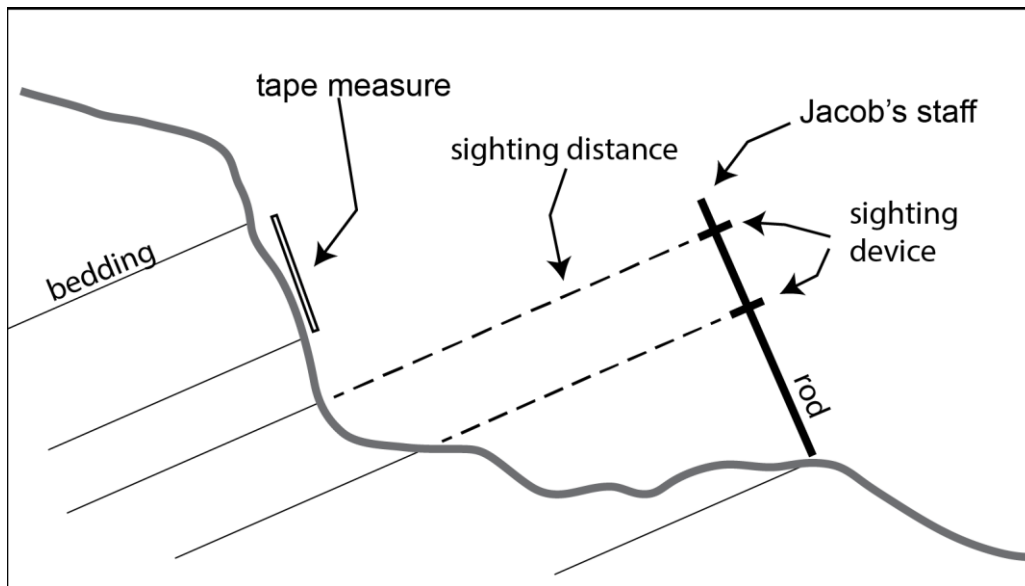
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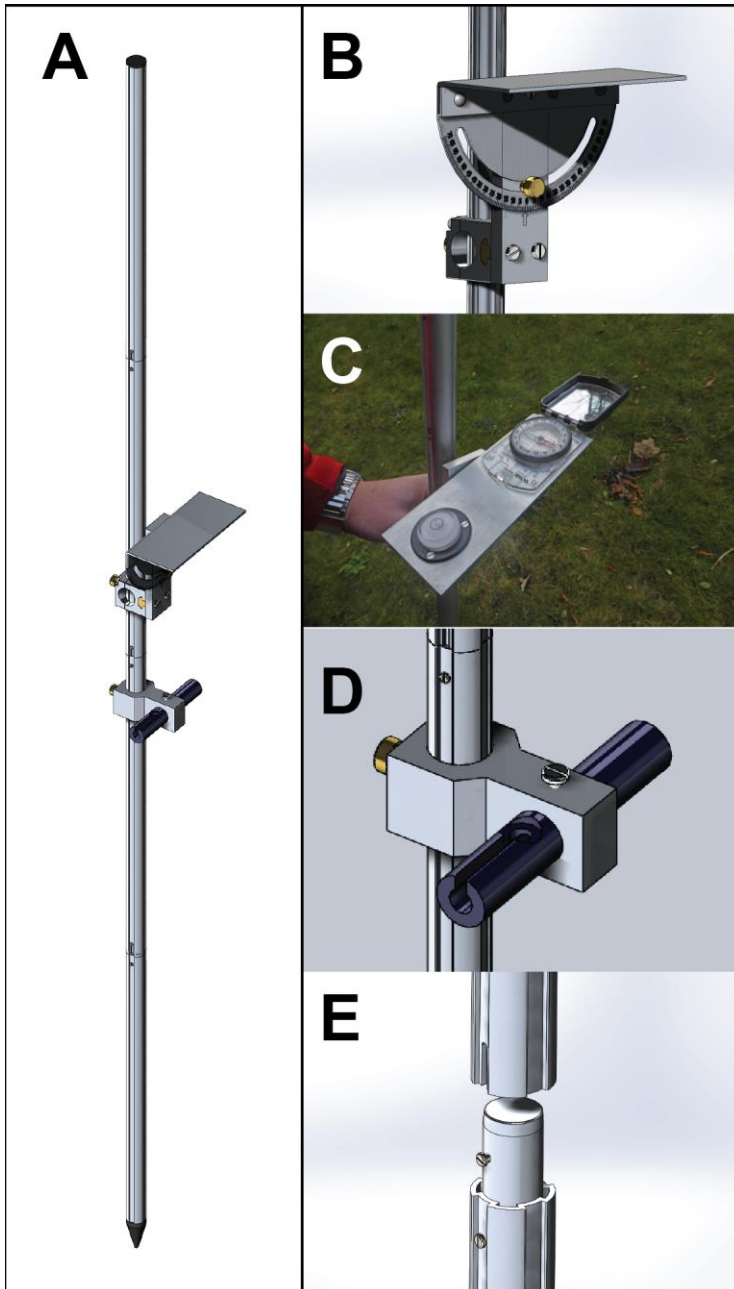
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253

254 Figure 1. A tape measure is an effective tool for measuring stratigraphic thicknesses when apparent
255 and real thicknesses tend to coincide (e.g., shallow dipping beds on a vertical cliff). When apparent
256 and real thicknesses of beds diverge (e.g., shallow dipping beds along a crest leading to a hilltop),
257 measurement must be carried out by sighting. In this scenario a Jacob's staff (comprising a rod and
258 sighting device) is the most effective tool for measuring stratigraphic thicknesses. Note that the
259 sighting device can be fixed (as in most traditional designs) or be able to move along the rod (as
260 shown here, in the new design).

261



262

263 Figure 2. A) The new Jacob's staff design. B-C) 3D positioning stage, including an angle gauge with
 264 the attached bracket holding a circular spirit level and a base plate compass (note that spirit level
 265 and compass are not shown in the technical drawings). D) Laser sighting stage (laser is not shown). E)
 266 Connecting mechanism between pieces of the rod. Technical drawings courtesy of Antony Windross.

267



268

269 Figure 3. The new Jacob's staff in action, measuring the stratigraphic thickness of the covered
270 interval between the top of the 'Lower Channel' and the base of the 'Upper Channel' at the
271 Monterosso outcrop (Gottero Sandstones, NW Italy). Photo courtesy of Marco Fonesu.