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Geological Orientation Measurements using an iPad: Method Comparison

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Abstract

This paper describes a tablet-based application to be used by novice geologists for taking geological measurements during fieldwork. The application was implemented on an iPad2. Both our app and the FieldMove Clino iOS app (from Midland Valley, a well-known geophysics software company) were compared with ground truth measurements taken using a Silva compass clinometer. The results show that the dip angle measurements taken using the iPad2 device are accurate, but dip direction measurements not of acceptable accuracy. However, the results indicate that the iOS Core Location method could be combined with multiple measurements to provide acceptable accuracy.

1. Introduction

Higher education institutions still rely on traditional tools such as geological notebooks and printed maps when taking students out for their fieldtrips. These traditional methods create difficulties for students and novice geologists comprehending geology they study in the field [WFD*09]. However, an increasing number of higher education institutions are convinced that the use of mobile technologies are fundamental to prepare students for their future careers [KER08].

This paper describes the background issues and the wider scope of the study, how iPad applications may be developed to take geological measurements from outcrops. It also evaluates our own prototype and an equivalent app from a well-known geophysics software company (Midland Valley). This provides the first controlled evaluation of the accuracy of such apps for fieldwork.

2. Background

Field trips are an essential part of teaching geology in higher education institutions. The tools and techniques for fieldwork have not changed for many years, and students often have difficulty *visualizing* geological structures using these tools and techniques [WFD*09].

The starting point for visualizing the underlying geology of an area by a novice geologist is developing a spatial understanding of the *outcrops* (visible parts of rocks). The finishing point is a 3D geological model of the field, produced by a repeated process of extrapolating and interpreting observations and measurements. Altogether, this is part of what geologists call “thinking in 3D” and has been acknowledged as “not necessarily easy come” [TM92].

In two field trips to Ingleton (North Yorkshire, England) we have observed first-hand the difficulties that students having extrapolating from outcrop measurement to 3D geological model. This laid the basis for the development of an iPad app for measuring and analyzing geological data by novice geologists. The proposed prototype is based on 3D visualization techniques aimed at assisting novice geologists carry out tasks out in the field.

2.1 Fieldwork tools

Like any other scientific field, geological fieldwork has been receiving a wave of new tools. These tools, and indeed traditional tools, can be divided into three categories: data capture, data viewing and data analysis.

The traditional tools such as compass clinometers belong to data capture. A printed map belongs to both data viewing and data analysis categories, whereas a stereonet is a 2D structural analysis tool.

Modern applications designed for fieldwork (mostly for professionals) tend to belong to the data capture and data-viewing categories. For example the FieldMove Clino by Midland Valley and RockLogger apps are mixtures of measuring, mapping and 2D stereonets analysis techniques.

These apps run on devices such as iPhones and iPads, which are equipped with sensors including magnetometers,

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gyroscopes and accelerometers. These sensors or chips known as MEMS (Micro-Electro-Mechanical Systems) enable these devices to determine device orientation [BPD11]. In addition, the devices' General Positioning System (GPS) sensors make it straightforward for students to determine their position, in our experience is error-prone and non-trivial task when performed using ordinary maps.

Therefore geological measurements such as *strike* and *dip* (defined next), using devices such as an iPad, unlike traditional tools, can be captured in one go without worrying about which way the device is oriented on an outcrop surface. Computational and graphics processing powers of these devices offer much more to learners out in the field.

2.2 Measuring orientation: strike and dip

The orientation of various structures is measured differently in different disciplines. In structural geology, the orientation of a planar structure such as a bedding plane of an outcrop is measured by recording “strike” and “dip” [PF05] (see Figure 1). *Dip* is determined by both *dip angle* and *dip direction* [TM92].

The *dip angle* is the angle between a bedding plane and the horizontal plane [TM92][PF05].

Strike is a horizontal angle with geographic north [TM92][PF05]. The *strike line* is a line formed by the intersection of a horizontal surface with inclined planar structure [TM92][PF05]. One of the two directions of this line can be used to record *strike*.

The *dip line* is defined as the direction of the steepest angle of a bedding plane, perpendicular to strike, and is also known as the *trend* by British geologists [TM92], this is called *dip direction* by [PF05] and throughout this paper.

The *dip direction* is also defined as the compass bearing of either of two opposite-facing planes for each strike line [TM92], measured in degrees and approximated to 45° segments (N, E, S, W, NE, SE, SW, NW) [TM92].

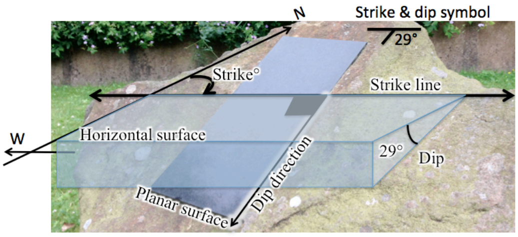


Figure 1 *Strike, dip and dip direction illustration using an inclined and a horizontal plane.*

Methods of measuring strike and dip using traditional tools such as a Silva compass clinometer is outlined by [BL04]. However, in the case of devices such as a compass clinometer the user has to align it in a particular way to take either strike or dip.

3. Technical implementation

Devices such as the iPad2 are equipped with sensors for various purposes. Manuals for determining compass headings using magnetometers are available from vendors [HO14]. However, iPad2 and similar devices come with their own Application Programming Interface (API) that contains recommendations for getting a compass heading.

This section describes the details of how dip angle and dip direction may be measured on an iPad2. To calculate dip angle we need to know the screen normal of the iPad2. To calculate the dip direction we also need to know the orientation of the iPad2 relative to north, for which there are two methods.

3.1 Measuring dip angle

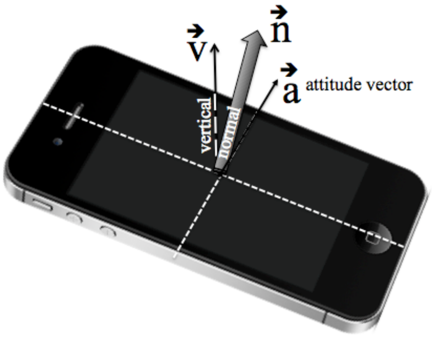


Figure 2 *Calculating normal vector to the screen of an iPhone using 3d vector arithmetic.*

Apple’s API’s Core Motion framework contains a class called CMAttitude (available from iOS5.0 onwards). This is given in the reference within which it was initialized, by default is set to x-axis pointing to geographic north.

In order to find dip angle and dip direction of a device first the normal vector to the screen of the device is required. The different vectors in relation to a device are shown in Figure 2.

The CMAattitude class contains various representations for the device *attitude*, including quaternions $[w(x,y,z)]$. Let the device attitude be defined by the quaternion q, its conjugate is $q' = [q_w\ (-q_x,-q_y,-q_z,q_w)]$, and the normal of the device when it is flat on the ground as quaternion $v = [0(0,0,1)]$. Indeed, the rotation of the current quaternion is equal to the rotation of v to current rotation quaternion q.

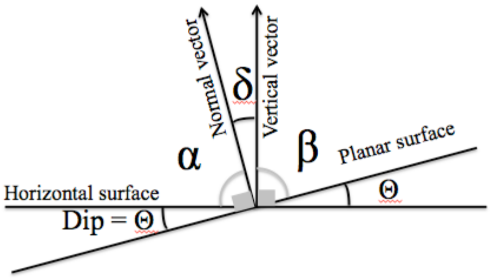


Figure 3 *Illustration of calculating dip angle as the angle between vertical and normal vectors of a plane.*

Applying quaternion rotation to a quaternion q, conjugate q' with a zero real number $(v) = q\ v\ q'$ [VIN07] [DEP96]. Thus, normal quaternion $n = q\ v\ q'$.

From Figure 3: $\delta + \alpha = 90$ & $\theta + \alpha = 90$ therefore $\delta = \theta$. Thus, the angle between the normal to the screen and the normal as the device is flat on ground quaternions equals the dip angle. The angle between present normal (n) and the flat on ground normal (v) quaternions (see Figure 2) can be calculated using the dot product of the two.

We can use the vector parts (x,y,z) of the quaternions n and v to calculate the two vector dot product.

$$\text{dip angle } (\Theta) = acos(n.v/|n|.|v|)$$

3.2 Measuring dip direction

For dip direction measurements two API libraries were used. Let's call them by the API names: Core Motion and Core Location.

Apple API gives the device attitude using Core Motion API, and a device "magnetic heading" in Core Location framework.

Having calculated the normal quaternion to the screen of an iPhone device, dip direction can be deducted. If as shown in Figure 4: $d(x,y,z)$ is the resulting dip direction 3d vector, $v(0,0,1)$ is the flat on ground vertical vector. Then using the vector part of the quaternion normal in the last section, a normal vector $n = (q_x,q_y,q_z)$.

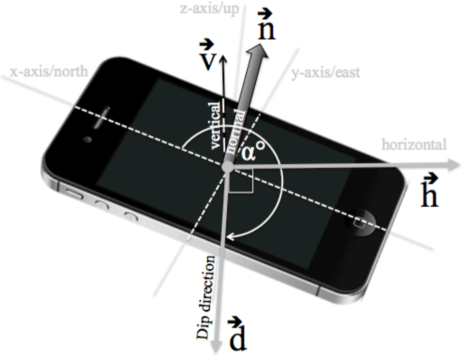


Figure 4 *Calculation of dip direction using Core Motion library.*

Using the right hand rule vector multiplication:

$h = v\ n$, h is on the device surface, then $d = h\ n$

The result vector (d) can be used to deduct the horizontal angle of rotation of the *x-axis*. This is because the *x-axis* of the vector was originally pointing to the north, the reference from which the dip direction is measured.

The arc tangent function of the result vector's (dy,dx) values is ±180 and is the dip direction angle form the north.

If $atan(d_y, d_x) < 0$, $\alpha = 180 + atan(d_y, d_x)$.

The second way of calculating dip direction is using the Core Location API. For device compass-heading Apple recommends a class called CLHeading (from iOS 4.0 onwards) in the Core Location API. This contains both a magnetic heading and true heading angles, magnetic heading is what we use.

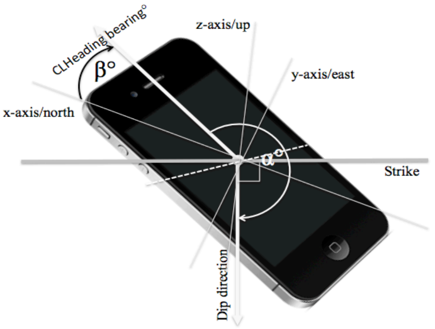


Figure 5 *Calculating dip direction using Core Location.*

This angle points to the direction from the centre of the screen to the top of the device as shown in Figure 5, lets call this β, but dip direction is $\beta + \alpha$.

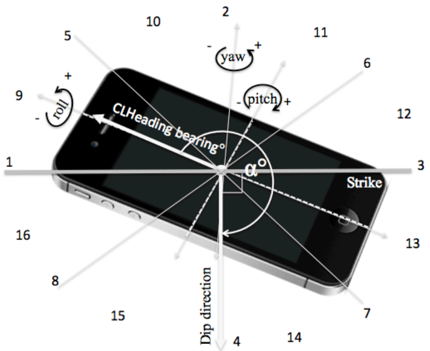


Figure 6 *iPhone body reference nautical angles as right-hand rule and 16 angles in relation to CLHeading.*

A	Pitch (p)	Roll (r)	Rt	$\beta + \alpha$
1	0	> 0	-	α - 90
2	> 0	0	-	α + 180
3	0	0 >	-	α + 90
4	0 >	0	-	α
5	$\|\|p\|\| = \|\|r\|\|$ & $p,r > 0$		-	α + 135
6	$\|\|p\|\| = \|\|r\|\|$ & $p > 0$ & $r < 0$		-	α - 135
7	$\|\|p\|\| = \|\|r\|\|$ & $p < 0$ & $r > 0$		-	α + 45
8	$\|\|p\|\| = \|\|r\|\|$ & $p,r < 0$		-	α - 45
9	$p,r < 0$ & $\|\|p\|\| > \|\|r\|\|$		p/r	(1) + Rt x 45
10	$p,r < 0$ & $\|\|p\|\| \|< \|\|r\|\|$		r/p	(2) - Rt x 45
11	$p < 0$ & $r > 0$ & $\|\|p\|\| > \|\|r\|\|$		p/r	(2) + Rt x 45
12	$p < 0$ & $r > 0$ & $\|\|p\|\| < \|\|r\|\|$		r/p	(3) - Rt x 45
13	$p < 0$ & $r > 0$ & $\|\|p\|\| < \|\|r\|\|$		p/r	(3) + Rt x 45
14	$p < 0$ & $r > 0$ & $\|\|p\|\| > \|\|r\|\|$		r/p	(4) - Rt x 45
15	$p,r > 0$ & $\|\|p\|\| > \|\|r\|\|$		p/r	(4) + Rt x 45
16	$p,r > 0$ & $\|\|p\|\| \|< \|\|r\|\|$		r/p	(1) + Rt x 45

Table 1 *All possible angles of dip direction using CLHeading class of Core Location*

As stated the device attitude is also given as Euler or Tait-Bryan angles (pitch, roll and yaw). The body reference of the device, the Euler angles and their rotations by right hand rules are shown in Figure 6.

There isn't a single mathematical formula to determine $\beta + \alpha$. There are 16 angles of β in relation to dip direction if the device is not vertical, as shown in Figure 6.

Angles 1 to 4 are known in Apple developer terms: portrait (opposite), inverse portrait (parallel), landscape with home button left (orthogonal right) or right (orthogonal left) respectively, where either pitch or roll is 0.

For angles 5, 6, 7 and 8 pitch and roll are equal. For the rest of the angles pitch and roll are non zero values which vary from 1, 2, 3 and 4 by a ratio of up to ±45°. For implementation convenience Table 1 includes the condition and answer for $\beta + \alpha$.

4. Evaluation

The evaluation compared the accuracy of dip angle and dip direction measurements made using iPad2 apps with ground truth measurements taken by an experienced geologist in the traditional manner, using a Silva Ranger 515 compass clinometer.

The two apps were: the *FieldMove Clino* iOS app (called FieldMove from here on), developed by Midland Valley, a well-known geophysics software company. The other was our *Prototype*, which used one method for calculating the dip angle and two methods (*Core Motion* and *Core Location*) for calculating the dip direction (see Section 3.2).

4.1 Method

4.1.1 Participants

An experienced geologist (Dr Douglas Paton, co-author) used a Silva Ranger 515 compass clinometer to take the ground truth measurements. Layik Hama (co-author) took the iPad2 measurements as he had similar experience with taking outcrop measurements as the target users for the app (novice geology students).

4.1.2 Materials

The School of Earth and Environment (SEE) at the University of Leeds has an area for undergraduate students to practice taking measurements based around Chancellor's Court. There are rocks with one or more pieces of flat various sized rectangular shapes fixed on them (Figure 1 shows one of them). Nineteen of these outcrops were used.

Both *prototype* and the FieldMove measurements were taken using the same Apple iPad2 tablet device running iOS 7.0.1. The prototype implementation is based on Objective-C, the native iOS language.

4.1.3 Procedure

For FieldMove and the prototype, three rounds of recordings were taken. During each round the dip angle and dip direction were measured four times, at compass readings of approximately 0°, 90°, 180° and 270°. For the prototype, both the Core Motion and Core Location methods were used for each measurement.

The dip and dip direction measurements from FieldMove app were taken by using the default settings of the app. Taking a measurement using the app requires a tap on the clinometer section of the app followed by "save" button.

4.2 Results and discussion

The following sections report the results for dip angle and dip direction.

4.2.1 Dip angle

The mean dip angle measurements for each outcrop are listed in Table 2. The signed error of each measurement was calculated by subtracting the app measurement from the ground truth. The mean signed errors were -0.56° (SD = 1.99) for the prototype, and 0.25° (*SD* = 1.97) for FieldMove. The error distributions are shown in Figure 7.

According to [WOO76] and a geologist in the School of Earth and Environment at the University of Leeds, an accuracy of 2° for dip angle is acceptable. For FieldMove 84% of the measurements satisfied this accuracy threshold, compared to 79% of the prototype measurements.

Outcrop #	Ground Truth°	FieldMove (average°)	Prototype (average°)
1	10	10	9
2	10	10	9
3	18	16	16
4	16	14	13
5	28	28	28
6	8	8	7
7	8	8	7
8	18	18	17
9	6	7	7
10	2	2	1
11	8	7	6
12	2	2	1
13	6	5	4
14	9	12	12
15	30	30	29
16	10	8	7
17	80	86	85
18	90	89	89
19	82	85	84

Table 2 *Mean dip angle of each outcrop.*

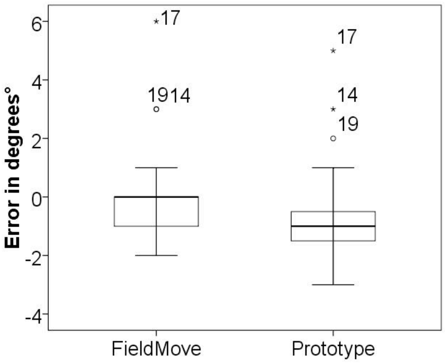


Figure 7 *Dip angle error distribution for FieldMove and the prototype. The asterisks show "extreme outliers" and the dots show "outliers", and the numbers next to the asterisks and dots correspond to the outcrop numbers. The box plot whiskers show the maximum and minimum values, excluding the outliers.*

4.2.2 Dip direction

Unlike dip angle, the dip direction measurements varied considerably from one reading to the next with FieldMove, with the prototype's Core Location and Core Motion methods. This is reflected in the magnitude of the errors, relative to the ground truth measurement.

For dip direction the research literature does not provide an acceptable error criterion, but the same geologist indicated that an appropriate criterion can be 5°.

The mean signed errors for FieldMove, Core Motion and Core Location were -12° (*SD* = 30), -10°(*SD* = 28), and -2°(*SD* = 28) respectively. The mean absolute errors for FieldMove, Core Motion and Core Location were 23° (*SD* = 23), 23°(*SD* = 19), and 21°(*SD* = 19) respectively. The mean error distributions are shown in Figure 8.

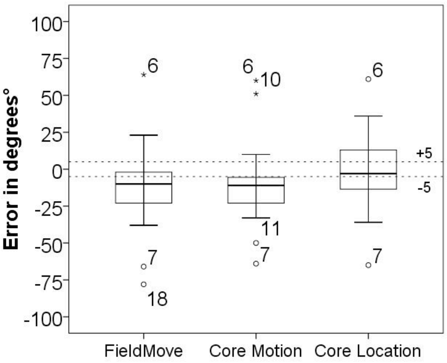


Figure 8 *Dip direction signed error distribution for FieldMove, Core Location and Core Motion. The asterisks show "extreme outliers", dots show "outliers", and the numbers next to the dots correspond to the outcrop numbers. The box plot whiskers show the maximum and minimum values, excluding the outliers. The acceptable error margin for dip direction readings is ±5°.*

The reasons for the large errors in the dip direction could be attributed to various reasons. One of the reasons could be the "ground truth" itself and the error from the Silva Compass. Taking a different set of measurements using a different compass or perhaps the same compass could be one way of exploring this further. The more likely reason could be the inherent inaccuracy of the magnetometer on the iPad device.

It is worth stating that the dip angle measurements were taken using the gyroscope chip only, whilst the dip direction measurements were taken using data from both the gyroscope and magnetometer chips.

In the case of the gyroscope, it is reported to be reliable and precise, but if the calculation requires more time and reliance on previous measurements it may become unreliable [SLM11]. This caution does not apply for taking dip measurements. Hence, the results confirm this and show that both the prototype and FieldMove readings are accurate and consistent (reproducible) for taking dip angles.

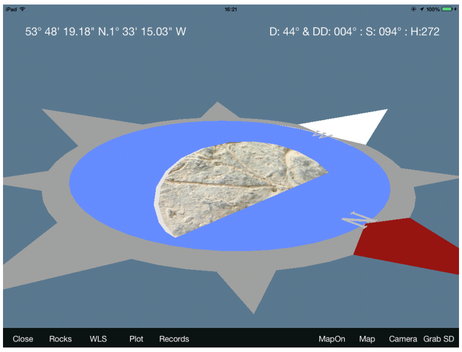
As for the magnetometer used for the dip direction measurements (regardless of the method), there is evidence that it performs according to the strength of the magnetic field it measures [BNH11].

Overall, the results show that the magnetometer is not at least consistent in reproducing the same recording for the same outcrop. It is also not accurate if accuracy is dictated by a 5° error margin.

5. Fieldwork app prototype

Based on the rationale in sections (3.1 and 3.2) a prototype was developed. The prototype is part of an app based on 3D visualization techniques as a solution to the spatial difficulties outlined in the background section of this paper.

A screenshot shown in Figure 9 shows how dip and dip direction can be visualized based on a widely used practical spatial cognition example by geologist educators known as "water level example" (WLE) [LT12].


53° 48' 19.18" N.1° 33' 15.03" W

D: 44° & DD: 004° : S: 094° : H:272

Figure 9 *iPad2 screenshot showing WLE simulation of captured dip and dip direction angles. The latitude & longitude numbers shows location, also dip angle, dip direction, strike and device heading angles in numbers.*

The concept of the WLE is what is effectively shown in Figure 1. Water (horizontal surface) touching a tilted rock surface forms the strike line, while the angle between the water surface and the dipping surface makes the dip angle. The dip direction is the direction of water trickling down the tilted surface. This is a technique recommended by

Liben and Titus as a technique for educators to assist students measure strike and dip [LT12].

The angles can always be shown in numerical figures as shown in Figure 9. One way to implement WLE is as follows: a half disc shape imitating a planar surface visualizes the dip angle relative to a horizontal (water) surface simulation whilst the dip direction is visualized relative to a compass. The strike would be either of the two directions of the line of intersection between the half disc and the water (horizontal).

6. Summary

Traditional tools and techniques for geological fieldwork have been creating issues for novice geologists and do not assist novice geologists visualize the spatial data they study. Scientific visualization based on mobile computing tools can help in addressing these issues.

An essential first step is to validate geological measurements made using such computing tools. This paper describes both the implementation of an iPad2 prototype app for making outcrop measurements, and the evaluation of that app and a similar one from a well-known geophysics software company.

Dip angle measurements were of acceptable accuracy, but dip direction measurements were not. However, the mean signed error data from our prototype app indicate that multiple measurements are made with the Core Location method then accurate dip directions may be measured. Use of that method would also improve the accuracy of Midland Valley's FieldMove app.

7. Acknowledgements

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