Comments on Moody's method for surface plate calibration

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The surface plate is a fundamental reference in precision measurement and metrology. Normally constructed from granite or cast iron, its top face should be as close to an ideal plane as possible. Early work by Whitworth [1] described how such a plane could be manufactured by scraping, starting with three non-planar surfaces.

Over the past century there have been many standards developed for characterizing the flatness of surface plates. One method commonly used is the "Union Jack" series of measurements described by Hume [2], which was then codified in a paper "How to calibrate surface plates in the plant", published by Moody [3] more than sixty years ago. The method uses tilt measurements along eight lines (two diagonal, four perimeter, and two center) as input. These are integrated and the linear trend is removed to obtain a surface profile. The name is used because the eight lines trace the outline of the United Kingdon flag.

Moody's paper is cited in engineering [4, 5, 6, 7, 8, 9, 10, 11], and vendor [12] literature. The paper contains an "algorithmic recipe" and set of worksheets for flatness determination. The measurements are carried out with an autocollimator (or a precision level) and entered into the worksheets, and then a specific recipe is given to analyze the data.

While superior methods now exist, and computers have replaced the manual worksheets, Moody's method is still widely applied. In part this is because of its simplicity and in part because it contains a pair of "closure" or consistency tests which quantify the magnitude of the measurement errors and uncertainties. In his recent book on machine tool metrology [9] Smith writes, "Of note, is that the Moody Method (i.e. Union Jack) is considered by many as the industry standard for calculating surface plate flatness. The method provides a simple but accurate means of assessing flatness and has been employed in metrology applications for many years."

The most widely cited current specifications for surface plates are US Federal GGG-P-463c [13], ISO 8512 standard [14] and ASME B89.3.7-2013 [15]. The first of these does not cite Moody's paper, but Section 4.5.9 (Flatness calibration and referee test) describes an 8-line procedure which is exactly Moody's method. Annex B of the ISO standard (Testing of Surface Plates) is remarkably vague. Section B.1, "Deviations from Flatness Overall" says that straightness may be tested "along various lines" either by comparison with a plate of known flatness, with straightedges, or using tiltmeters or optical instruments such as autocollimators. But no significant detail is given.

The purpose of this brief paper is two-fold. First, to correct typos, omissions, and misstatements from Moody's paper, and second, to provide and document a simple portable public reference implementation (in standard ANSI C) of Moody's algorithm. This code is equivalent to Moody's worksheets.

What follows here assumes that the reader has a copy of Moody's paper [3] in hand. We begin by addressing the significant omissions and corrections:

The first comment concerns the location of the measuring stations. Moody specifies that the foot spacing of the mirror mount should be about 8% of the short side of the plate (in his example, about 4 inches) and calls this quantity the "increment". He specifies that the perimeter lines should be laid out one increment from the edge of the plate, and that the precise stations at which readings are taken are measured off in steps equal to the increment along the straight lines. Later, Moody writes that "No reading is entered for the first station on the line". This might be incorrectly interpreted to mean that the first reading taken with the autocollimator should be discarded from the data analysis procedure. No autocollimator readings should be dropped or discarded. **Autocollimator readings should be taken with the mirror mount placed symmetrically between stations, with one foot just touching one station and the other foot just touching the adjacent station. Each readings should be entered into the worksheet next to the larger numbered station. Thus, the number of readings is one less than the number of stations.**

The second concerns the overall "sign" of the angular deviations which are the input to the worksheets; Moody never specifies a convention for this. The output of the worksheets is a map showing height deviations from flatness, but if the overall sign of the input measurements is accidentally reversed, then a surface plate which is concave would mistakenly be mapped as convex. **The sign convention used in Moody's paper is that the angular deviation becomes more positive when the top of the reflector mirror is tilted towards the first station on each of the eight lines.** If the autocollimator or tiltmeter has the opposite convention, then the signs of all angles should be reversed.

The third comment is closely related. In order for Moody's methods to work, the signs associated with each of the eight measured lines must be consistent with one another. Figure 3 of Moody's paper was intended to show the correct position of the autocollimator for each line, but both it and related text are ambiguous. **The autocollimator may be placed at either end of the line, provided that the sign convention in the previous comment is followed.** For example if the autocollimator beam enters by the first station on the line and exits after the last station on the line, then the angular deviation should become more positive when the top of the reflector mirror is tilted towards the autocollimator. If it is more convenient to place the autocollimator so that its beam traverses the line in the opposite direction, and the autocollimator output becomes more positive when the top of the reflector mirror tilts towards it, then the signs of all of the angular measurements along that line should be reversed, so that the angular deviation becomes more positive when the top of the reflector mirror is tilted away from the autocollimator (i.e., towards the first station along the line).

The fourth comment concerns the subtraction leading to column 7 of the worksheets ("Displacement from the Base Plane"). The text says to find the lowest (smallest) value in column 6 or 6a from all eight worksheets, and then to add that value to that given in column 6 or 6a and to enter this into column 7. This is incorrect. **The lowest value in column 6 or 6a from all eight worksheets must be subtracted from column 6 or 6a to obtain column 7.**

A fifth comment concerns the overall size of the plate which is calibrated in Moody's example. Table 1 carries the title "Worksheets for Calibrating a 48 x 78-Inch Surface Plate". The diagonal length of such a plate would be slightly less than 92 inches. However the first and second worksheets indicate diagonal stations beginning at 3 inches and ending at 83 inches. That is consistent with a 48 x 72 inch surface plate (also a US standard size [13]) which has an 86.5-inch diagonal. **The title of the Table 1 should be "Worksheets for Calibrating a 48 x 72-Inch Surface Plate".**

A sixth comment concerns arithmetic mistakes in the example worksheets that Moody presents, because in places where the text is hard to follow, the worksheets serve as a model.

- In worksheet 2 (NE-SW diagonal) columns 2 and 3 are inconsistent by station 79. Either column 2 should read 43 arcsec (rather than 42) or column 3 should read -24 arcsec (rather than -23).

The table is consistent and correct if column 2 is changed to 43 arcsec.

- In worksheet 3 (NE-NW perimeter) columns 2 and 3 are inconsistent by station 40. Either column 2 should read 188 arcsec (rather than 183) or column 3 should read -22 arcsec (rather than -17). The table is consistent and correct if column 2 is changed to 188 arcsec.

- In worksheet 6 (NW-SW perimeter) the station 8 displacement listed in column 8 should be 70 rather than 40 microinches.

Note that there is also some incorrect rounding affecting columns 7 and 8 in several of the worksheets, but since these are in the final decimal places they are not confusing.)

Lastly, the description given by Moody of the consistency check is somewhat vague . A clearer statement is the following. **After the East to West Center Line has been constructed, examine the value of column 6 at the central station. In the absence of any measurement or numerical errors, this value would be zero. If it is nozero, convert it to a distance by multiplying the angle in radians [1] by the mirror mount foot spacing. If this distance error is larger than 100 microinches (2.54 microns) then the measurements and calculations should be repeated[2].** This check should also be carried out for the North to South Center Line.

In the text Moody mentions "moving the error out from the center". This refers to the case where one or both of the center lines have non-zero deviations from the base plane in column 6 at the central station. In this case, since internal consistency requires a zero value, one can displace the entire line of measurements upwards or downwards to make them zero at the central station. This however means that they no longer match the values at the center of the perimeter boundaries. Column 6a gives the heights along this shifted line. (Note that it is not clear why the resulting inconsistency at the boundary is prefered to one at the center. An intermediate shift that minimized the sum of the squared errors are the center and boundaries might be more sensible.)

The supplementary materials for this note include a a standard ANSI C reference code implementation of Moody's worksheets. This is portable to virtually any computing environment. For ease in compiling and distribution, the code is contained in a single file. It takes as input a configuration text file, and eight text data files, one for each of the eight measured paths. These files should have one line for each angular measurement, containing the value in arcsec. A set of text files corresponding exactly to Moody's paper (with the corrections given above) is provided as test input data. The code outputs the completed worksheets as Moody published them and also correctly handles the cases where there are an even number rather than an odd number of measurement stations along one or more of the lines. The README file which is provided documents how the code can be run, and the available options.

[1] One arcsecond is $2\pi/(360 \times 60^2)$ radians $= 4.848 \times 10^{-6}$ radians.

[2] The arbitrary value of 100 microinches is taken verbatim from Hume [2] and does not depend upon the size of the plate. Hermann [10] has a more rational and justifiable approach to this error analysis.

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