Practical Astronomy with your Calculator or Spreadsheet

Fourth Edition

Now in its fourth edition, this highly regarded book is ideal for those who wish to solve a variety of practical and recreational problems in astronomy using a scientific calculator or spreadsheet.

Updated and extended, this new edition shows you how to use spreadsheets to predict, with greater accuracy, solar and lunar eclipses, the positions of the planets, and the times of sunrise and sunset. With clear, easy-to-follow instructions, shown alongside worked examples, this handbook is essential for anyone wanting to make astronomical calculations for themselves. It can be enjoyed by anyone interested in astronomy, and will be a useful tool for software writers and students studying introductory astronomy.

- Gives easy-to-understand, simplified methods for use with a pocket calculator.
- Covers orbits, transformations and general celestial phenomena, for use anywhere, worldwide.
- High-precision spreadsheet methods for greater accuracy are available at www.cambridge.org/practicalastronomy.

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To our friends and
colleagues at MRAO

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Preface to the fourth edition

Practical Astronomy with your Calculator or Spreadsheet has been written for those who wish to calculate the positions and visual aspects of the major heavenly bodies and important phenomena such as eclipses, either for practical purposes or simply because they enjoy making predictions. We present recipes for making calculations, where we have cut a path through the complexities and difficult concepts of rigorous mathematics, taking account only of those factors that are essential to each calculation and ignoring corrections for this and that, necessary only for very precise predictions of astronomical phenomena. Our simple methods, suitable for use with a pocket calculator, are usually sufficient for all but the most exacting amateur astronomer, but they should not be used for navigational purposes. For example, the times of sunrise and sunset can be determined to within 1 minute and the position of the Moon to within one fifth of a degree. But new to this fourth edition are spreadsheets which offer much higher precision (see below).

The second edition included much more material in response to letters and requests from readers of the first edition. Many errors were also corrected. The third edition continued the same process, adding four new sections on generalised coordinate transformations, nutation, aberration and selenographic coordinates, improving the sunrise/set and moonrise/set calculations so that they worked properly everywhere in the world, including a rigorous method of calculating precession, taking account of the J2000 astronomical system where appropriate, and correcting mistakes or clarifying obscurities wherever they were found in the second edition.

The fourth edition has also been updated considerably; however the major change is that we have included, for the first time, a spreadsheet for nearly every calculation. Each spreadsheet illustrates the calculation, making it easier to get the right answer. But we have also written a library of powerful functions which can carry out many of the calculations for you with much higher precision, so those people who wish to use their computers can do so and obtain the benefits of greater accuracy. For example, use the simple recipes and your calculator to find the times of moonrise and moonset to within a precision of 10 minutes or so, or use the spreadsheet functions to obtain the results correct to within 1 minute. You will need to visit our website (see page 209) to download the spreadsheets to your computer; the library of functions will come automatically with the spreadsheets.

We are most grateful to those kind people who have taken the trouble to write in with their suggestions, criticisms and corrections, in particular to Mr E. R. Wood, who kindly scanned the manuscript of the third edition for errors, Mr S. Hatch, Mr S. J. Garvey, who supplied the nomogram for the solution of Kepler's equation, and Mr Anthony Ehrlich of Pittsburgh, Pennsylvania, who developed a rudimentary scheme for calculating the circumstances of sunrise/set and moonrise/set into one that actually worked

(superseded in this edition). We would also like to thank and acknowledge those authors whose books we have read and whose ideas we have cribbed, mentioning particularly Jean Meeus (*Astronomical Formulae for Calculators*) and W. Schroeder (*Practical Astronomy*). We have made extensive use of *The Explanatory Supplement to the Astronomical Ephemeris* and the *American Ephemeris and Nautical Almanac*, as well as the *Astronomical Almanac* and its predecessors.

Our thanks are also due to Dr Anthony Winter, who suggested writing the first edition of the book, to Mrs Dunn who typed it, to Dr Guy Pooley who read the manuscript and made many helpful suggestions, and to Dr Simon Mitton for taking so much trouble over the production of the book. Thanks for particular help with the fourth edition go to William Lancaster, Sehar Tahir and our editor Vince Higgs.

We are most grateful to Gary Barnes, Allan Bell, Markus Böhm, Michael Coren, Mike Dworetsky, Errol Glaze, Greg Halac, Ilja Heckmann, John Horsman, Stuart Lowe, Henry Nilsson, Graham Relf, J. Sapranidis and Mike Trace for spotting errors in the initial versions of the text and in the spreadsheets and their functions.

We hope you have as much fun with these recipes and spreadsheets as we have had! Please let us know when you find an error. You can contact us via the book's website (see page 209).

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About this book and how to use it

How many times have you said to yourself, 'I wonder whether I can see Mercury this month?' or 'What will be the phase of the Moon next Tuesday?' or even 'Will I be able to see the solar eclipse in Boston?' Perhaps you could turn to your local newspaper to find the information, or go down to your local library to consult the *Astronomical Almanac*. You may even have an astronomical journal containing the required information, or perhaps some computer software or a website that might do the trick. But you would not, we suspect, think of sitting down and calculating it for yourself. Yet even though you may not find mathematics particularly transparent, you can still do this for yourself. You can quite easily find the answer to many astronomical questions using this book of calculation recipes. You use it just as you would a recipe book in the kitchen – follow the recipe and produce a delicious dish! All you need in addition is a calculator, a piece of paper, a ruler and a pencil. (For those of us with access to a computer, we can use that instead of the calculator and carry out all the calculations in a spreadsheet program as further described below.)

Your calculator does not have to be a very sophisticated device costing a great deal of money; on the other hand it should be a little better than a basic four-function machine. At a minimum, it must have buttons for the trigonometric functions sine, cosine and tangent. It should also be able to find square roots and logarithms. Such calculators generally describe themselves as 'scientific calculators'. Features other than these are not essential but can make the calculations easier. For example, having a number of separately-addressable memories in which you can store intermediate results would be useful. If you have a programmable calculator, you can write programs to carry out many of the calculations automatically with a subsequent saving of time and effort.

When choosing a calculator, don't be led astray by arguments about whether 'reverse Polish notation' (RPN) or 'algebraic notation' (AN) is the better system. Each has its advantages and the same complexity of calculation may be made using either. It is important, however, to read the instructions carefully and to get to know your calculator thoroughly, whatever system it uses. Make sure that you like the 'feel' of the keypad, and that pressing a key once results in just one digit appearing in the display. Look out for special functions that can help you, like a key that gives you π (the constant 3.141 592 654), a key that converts between times or angles expressed as hours or degrees, minutes, and seconds, and their decimal equivalents, a key that takes any angle, positive or negative, and returns its equivalent value reduced to the range 0° to 360°, and a key that converts between rectangular and polar coordinates (very useful for removing the ambiguity of 180° on taking the inverse tangent of an angle).

When you go through the worked examples given with each calculation, do not be alarmed if your figures do not match ours exactly. There are several reasons why they may not, including rounding errors and misprints. You should try to work with at least seven or eight significant figures. If you write your own programs to carry out any of the calculations on a computer, make sure that you use variables having sufficient resolution. Use double precision (eight-byte precision) everywhere if possible.

Having gathered together your writing materials, calculator and book, how do you proceed? Let us take as an example the problem of finding the time of sunrise. Turn to the index and look up ‘sunrise’; you are directed to page 112 where you will find a paragraph or two of explanation and a list of instructions with a worked example in the form of a table. We have kept things brief on purpose and have made no attempt to provide mathematical derivations. We have also simplified the calculations. As you work through each step, write down the step number and the result in a methodical fashion. Take care here and it will save you a lot of time later!

Many calculations require you to turn back and forth between different sections. For example, step 1 of ‘sunrise’ directs you to another section to calculate the position of the Sun. Make the calculations in that section, and then turn back to carry on with step 2. You will find it useful to keep several slips of paper handy as bookmarks.

This book is not intended to match the precision of the results found in the *Astronomical Almanac*. As we have already mentioned, the calculations have deliberately been simplified although they are good enough for most purposes. If you have your own computer, you can use the methods to write programs displaying the evolving Solar System with a precision that is better than the resolution of the computer screen. But those of us with simple pocket calculators can find great satisfaction in simply being able to work out the stars for ourselves and to predict astronomical events with almost magical precision.

A word about spreadsheets – what are they?

In 1979, when the first edition of *Practical Astronomy with your Calculator* was published, very few people had access to a computer. Although home computers were beginning to appear in the high street, they were not the commonplace household accessory we see today. Calculations were made using a calculator, the sophistication of which ranged from the simple four-function device to the versatile programmable reverse-Polish scientific machine. You may already own a calculator that would be suitable for the recipes given here, but you might also own a computer and wish to make the calculations using that instead. If you are good at programming, you could consider using the methods described in this book as a basis for writing your own astronomical software. But most of us don't want to embark on such a project. How then can we use our computers to make astronomical calculations?

One answer is to use a **spreadsheet** program such as Microsoft's *Excel*, or OpenOffice *Calc*. The latter is available at no cost, and described as fully compatible with the former, so if you do not already own a commercial spreadsheet program, then *Calc* might be a good way to go. Once you have loaded the software on to your machine, open the spreadsheet program. The screen display should then look something like Figure I. (Here and throughout the book, toolbars, sidebars and many other features have been removed from the spreadsheet views.)

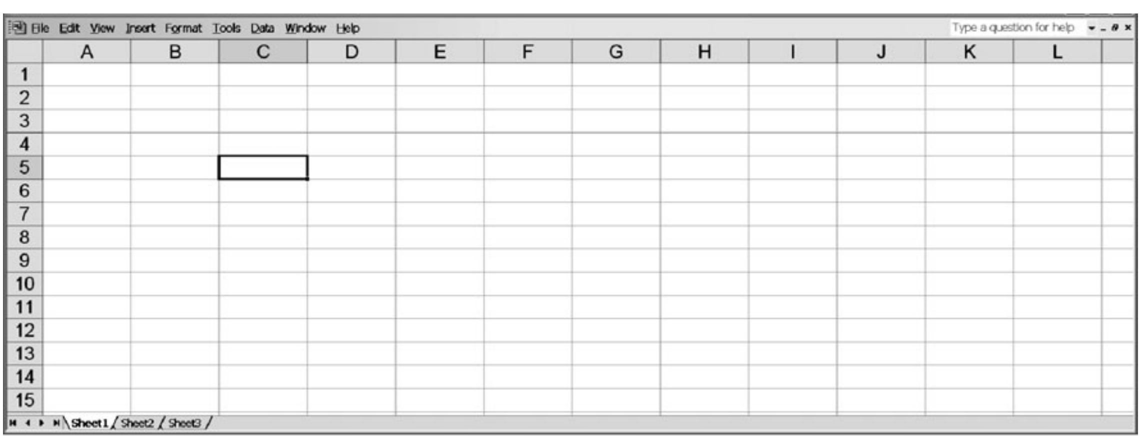

Figure I. An empty spreadsheet.

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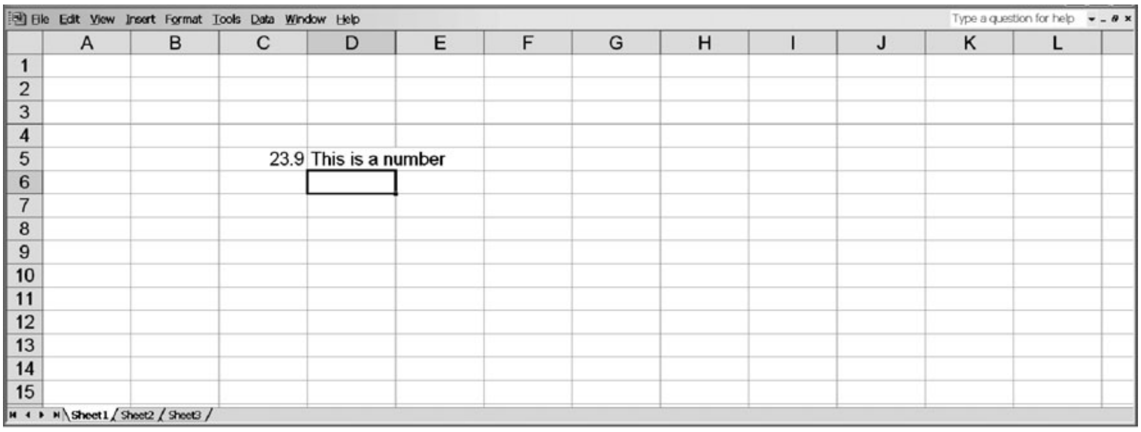

Figure II. Cell C5 carries the number 23.9, and cell D5 carries the label This is a number.

The spreadsheet consists of an array of cells, labelled A, B, C etc. across the top (these are the column labels) and 1, 2, 3 etc. down the left-hand side (these are the row labels). Each individual cell is labelled by its column letter and its row number, e.g. A1, B25 etc. The cell with the thick border around it in Figure I is cell C5. You can write some text or numbers in any cell. In Figure II, the number 23.9 has been placed in cell C5, and the label This is a number has been placed in cell D5. (Since cell E5 is empty, the program has allowed the label to overwrite the space allocated to E5, although the entire content This is a number remains in D5, and E5 remains empty.) The spreadsheet knows that something placed in a cell is a label (i.e. text) if you begin the entry with a single apostrophe symbol ('). If you want to enter a number as a number, just type it in. If you want the spreadsheet to treat the number as a label, put the apostrophe in front of it.

We can obviously put labels and numbers in any of the cells, but the real power of the spreadsheet comes from using formulas. A formula is a calculation which can use the contents of other cells. The result of the calculation is displayed in the cell carrying the formula, so you are not usually aware of the calculation that has gone on in the background since what is displayed is the result rather than the formula itself. A formula is placed in a cell by typing the equals sign (=) followed by the formula. The spreadsheet knows from the equals sign that it is to calculate the formula and display the result. For example, in Figure III, cell C6 carries the entry =C5*C5. You will see that C6 now displays the result of multiplying the number in cell C5 by itself (the star symbol * means 'multiply'), i.e. the square of the number 23.9, which is the number 571.21. We have also placed the label This is its square in cell D6.

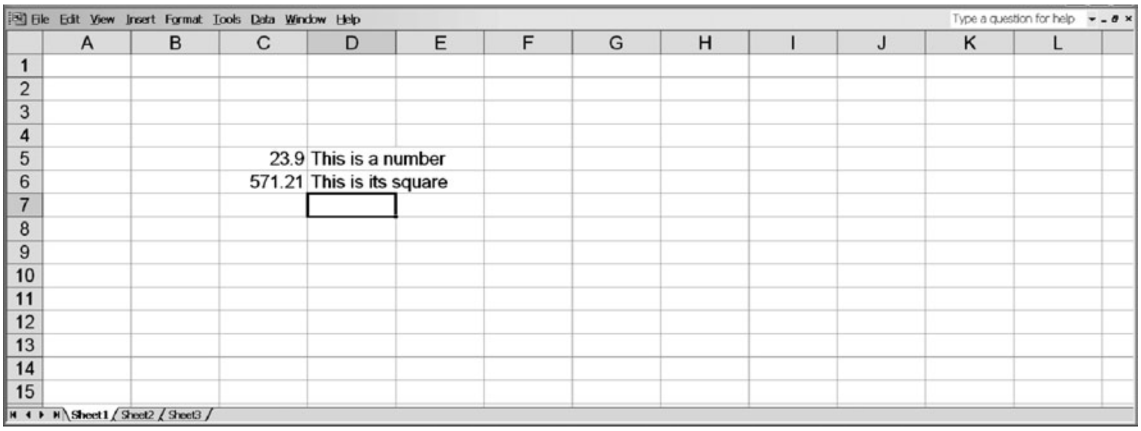

Figure III. Cell C6 carries the formula =C5*C5 and hence displays the square of 23.9.

Let's see what happens if now we change the number in cell C5 without making any other change to the spreadsheet. In Figure IV the number in C5 has been changed to the number 4.0 and, hey presto, the square of 4 (i.e. 16) is displayed in cell C6. You can begin to see that complex calculations can be performed for you automatically with a spreadsheet program. With the right formulas placed in order in the spreadsheet, the results can be calculated for any set of starting values. That is just what we want to do in this book. We can hide the complications of the calculation of, say, the time of sunrise within the formulas and just enter a date and geographical location in the correct cells at the top to obtain the result immediately.

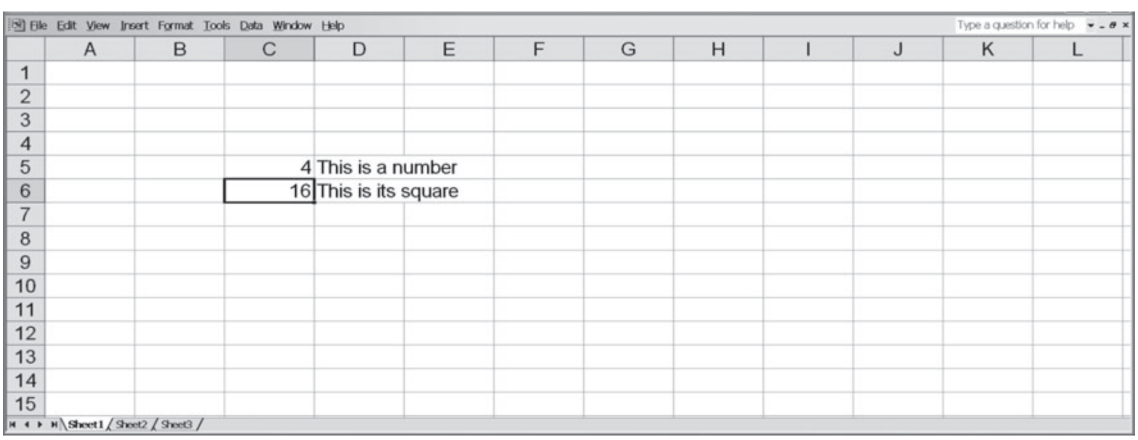

Figure IV. Cell C5 now carries the number 4 and so cell C6 displays the number 4 multiplied by 4 which is 16.

We don't need to explain much more about spreadsheets here, although we will note various techniques as we go along. If you want to learn more about their powerful capabilities we suggest buying a book about spreadsheets (see the Bibliography on page 208 for a suggestion). In this book, we have supplied you with the spreadsheet and formulas for most calculations, so all you have to do is to type in the labels, numbers and formulas as shown. The spreadsheet will then do its work automatically and give you the answer for any starting values you enter. (We have provided the spreadsheets ready-made on our website. Please look in the section “A useful website” on page 209 for details.)

The layout of spreadsheets in this book

All of the spreadsheets in this book conform to the same general format (see Figure V). At the top, in cell A1, is the title of the spreadsheet (in this case Converting decimal hours to hours, minutes and seconds). It is best to use a slightly larger font size for this and to make it boldface as here. We have used Arial 16 point for the title. Row number 2 is left blank (i.e. none of the cells has anything in it). In row 3, we have written the label *Input* in A3 (Times New Roman font, italic face, 10 point) to remind us that the input values for the spreadsheet are entered to the right of this cell. In the case shown in Figure V, there is only one input value, the decimal hours (name label in B3, Arial font, bold face, 14 point), and it is entered in cell C3 (also Arial font, bold face, 14 point). In spreadsheets which have more than one input value, the others have their name labels in cells B4, B5 etc. and their corresponding values in C4, C5 etc.

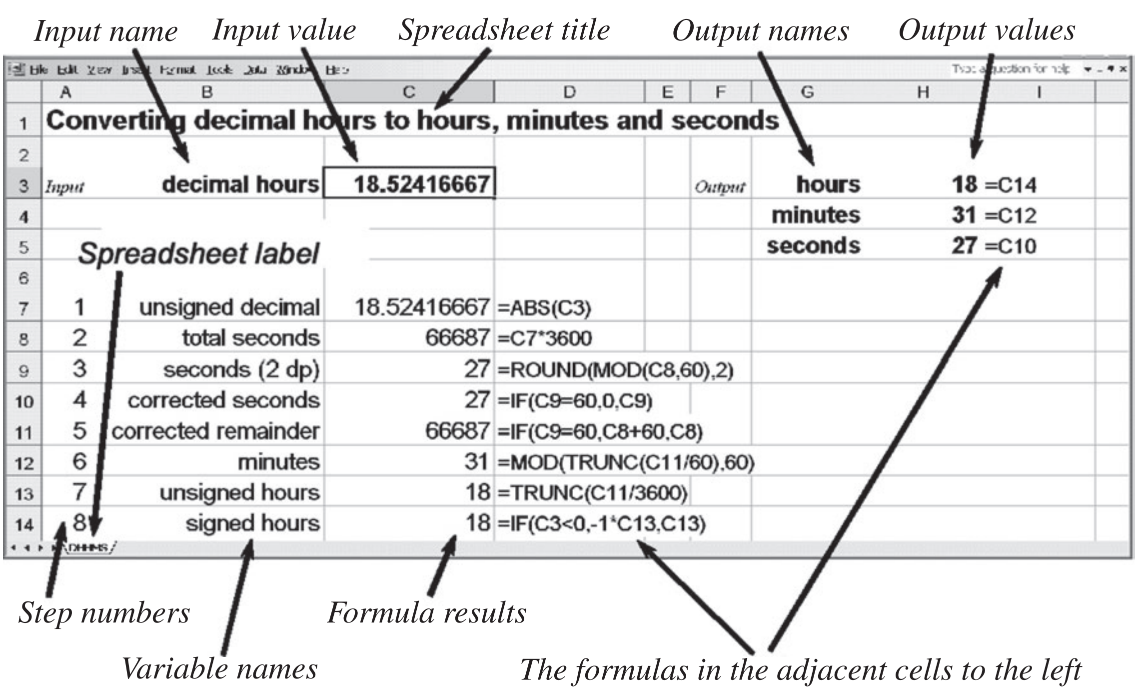

Figure V. The layout of a spreadsheet.

The results of the calculations, i.e. the output values, are provided to the right of cell F3. We have written the label *Output* in F3 (Times New Roman font, italic face, 10 point) to remind us that the output values calculated by the spreadsheet appear to the right of this cell. In the case shown in Figure V there are three output values, called hours, minutes, seconds. Their name labels appear in cells G3, G4, G5 (Arial font, bold face, 14 point) and their values in H3, H4, H5 (also Arial font, bold face, 14 point) respectively. Just to the right of the three output values, in column I, are shown the formulas (written as labels, i.e. with an apostrophe in front of the equals sign to stop the program calculating the formula) that are actually in the output value cells. Thus cell H3 actually contains the formula =C14 (i.e. it will display the value of the cell C14) and you will need to enter =C14 in the cell H3. Wherever you see a formula (anything beginning with the equals sign) enter exactly that formula in the cell immediately to its left. In this case you would put =C14 in cell H3, =C12 in cell H4, and =C10 in cell H5.

The calculations carried out by the spreadsheet begin on row 7 in Figure V. Each row corresponds to one step in the calculation, in this case the calculation method of Section 8. In the method table shown in that section there are just two steps, whereas in the spreadsheet there are eight. There is only a rough correspondence between method steps and spreadsheet steps. This is partly because the spreadsheet calculations do not have the benefit of human intelligence to assist them! For example, if you used your calculator to carry out the steps of Section 8, and you found that the result was, say, 6h 35m 60s, you would automatically write this as 6h 36m 0s. The spreadsheet would, however, quite happily report the result in the first format. We get over the problem in the spreadsheet by first stripping out the sign, then converting to seconds, then finding the seconds, minutes and hours in that order, and finally putting back the sign.

In the example shown in Figure V, you would enter the labels and formulas exactly as shown. Thus on row 7 you place the label '1 in A7 (this is text, and the apostrophe tells the spreadsheet so), the label 'unsigned decimal in B7 and the formula in C7 shown immediately to its right, i.e. =ABS(C3). Do this for each calculation row (7 to 14 in this case). Finally, rename the spreadsheet on the tab at the bottom (DHHMS in this case). (You can probably do this by pointing at it with the mouse, pressing the right-hand mouse button, and selecting the 'rename' option.)

Although the labels in columns A and B make no difference to the calculations, we recommend that you put them in as they make the spreadsheet much easier to understand. This becomes more important if you return to a spreadsheet some time after you constructed it.

One other note about spreadsheets that you might find useful concerns column widths. If the column width is too narrow to display the content of a cell, you may just see something like ######## displayed instead. You can adjust the column width by placing the mouse pointer on the division between the label (A, B, C etc.) of the column you want to alter and the label of the column immediately to its right, holding down the left-hand mouse button, and 'dragging' the column width left or right as needed.

Calculations involving multiple sheets

Some of the spreadsheet calculations, as in the example just given, use just one sheet. Most, however, use several. For example, suppose that a first spreadsheet calculation results in a number expressed in decimal hours but the answer has to be in the form hours, minutes and seconds. The first sheet passes its answer (in decimal hours) to a second sheet which carries out the conversion and passes the converted result back again to the first sheet.

A concrete example is illustrated by a spreadsheet for Section 14, reproduced in Figure VI. You will see that there are three tabs in the bottom left-hand corner, corresponding to three sheets labelled GSTLST, HMSDH and DHHMS. Only the top sheet, GSTLST is visible in the figure with the other two lying 'underneath' it. The input values to the calculation include the Greenwich sidereal time (GST) expressed in hours, minutes and seconds (cells C3, C4 and C5). These must first be converted to the GST expressed in decimal hours, a calculation covered in Section 7. The spreadsheet for that section, labelled HMSDH, must

	A	B	C	D	E	F	G	H	I
1	**Conversion of GST to LST**								
2									
3	*Input*	**GST hours**	**4**			*Output*	**LST hour**	**0**	=C12
4		**GST mins**	**40**				**LST min**	**24**	=C13
5		**GST secs**	**5.23**				**LST sec**	**5.23**	=C14
6		**geog long**	**-64**						
7									
8	1	GST	4.668119444	=HMSDH!H3					
9	2	offset	-4.266666667	=C6/15					
10	3	LST (hours)	0.401452778	=C8+C9					
11	4	LST (hours)	0.401452778	=C10-(24*INT(C10/24))					
12	5	LST hour	0	=DHHMS!H3					
13	6	LST min	24	=DHHMS!H4					
14	7	LST sec	5.23	=DHHMS!H5					

Figure VI. A spreadsheet with multiple sheets.

	A	B	C	D	E	F	G	H	I
1	**Converting hours, minutes and seconds to decimal hours**								
2									
3	*Input*	**hours**	**4**	=GSTLST!C3		*Output*	**decimal hours**	**4.668119444**	=C10
4		**minutes**	**40**	=GSTLST!C4					
5		**seconds**	**5.23**	=GSTLST!C5					
6									
7	1	*A*	0.087166667	=ABS(C5)/60					
8	2	*B*	0.668119444	=(ABS(C4)+C7)/60					
9	3	*C*	4.668119444	=ABS(C3)+C8					
10	4	*D*	4.668119444	=IF((C3<0)+(C4<0)+(C5<0),-C9,C9)					

Figure VII. Illustrating cross-references between sheets.

be included in this spreadsheet file as an additional sheet – the tab HMSDH in Figure VI. Figure VII shows the spreadsheet with the HMSDH sheet on top so it is visible.

The link between the sheets is accomplished by using the sheet name, followed by an exclamation mark (!) and the cell reference. In Figure VII, the input value of hours (C3) is obtained from cell C3 of sheet GSTLST by using the formula =GSTLST!C3. Similarly, the input value of minutes is obtained using the formula =GSTLST!C4 in cell C4 of HMSDH, and the input value of seconds is obtained by using the formula =GSTLST!C5 in cell C5. The result of the calculation by this sheet, the decimal hours, appears in cell H3

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of Figure VII. This is passed back to sheet GSTLST in cell C8 of Figure VI, which contains the formula =HMSDH!H3.

Similarly, the result of the calculation of GSTLST, expressed in decimal hours, appears in cell C11 of Figure VI. This needs to be converted to the format hours, minutes and seconds and it is passed to sheet DHHMS (see Figure VIII) by using the formula =GSTLST!C11 in cell C3 of that sheet. Sheet GSTLST then extracts the results from sheet DHHMS (H3, H4 and H5 of Figure VIII) using the formulas DHHMS!H3, DHHMS!H4 and DHHMS!H5 respectively in cells C12, C13, and C14 of Figure VI.

	A	B	C	D	E	F	G	H	I
1	**Converting decimal hours to hours, minutes and seconds**								
2									
3	*Input*	decimal hours	0.401452778	=GSTLST!C11		*Output*	hours	0	=C14
4							minutes	24	=C12
5							seconds	5.23	=C10
6									
7	1	unsigned decimal	0.401452778	=ABS(C3)					
8	2	total seconds	1445.23	=C7*3600					
9	3	seconds (2 dp)	5.23	=ROUND(MOD(C8,60),2)					
10	4	corrected seconds	5.23	=IF(C9=60,0,C9)					
11	5	corrected remainder	1445.23	=IF(C9=60,C8+60,C8)					
12	6	minutes	24	=MOD(TRUNC(C11/60),60)					
13	7	unsigned hours	0	=TRUNC(C11/3600)					
14	8	signed hours	0	=IF(C3<0,-1*C13,C13)					

Figure VIII. Illustrating cross-referencing between sheets.

Now you can proceed in this way if you wish, using multiple sheets to carry out specific calculations as just described, but the result can be quite confusing when you have a complicated calculation requiring many sheets. A better way to proceed is for us to define our own functions and use these instead to carry out the calculations. This is the approach that we have adopted here.

Using our own functions

Microsoft *Excel* and OpenOffice *Calc* both come with an internal programming language called BASIC. We don't need to go in to any of the details of what this is and how it works, but suffice it to say that we have written functions to carry out most of the calculations described in this book. All you have to do is to use the functions in your spreadsheet exactly as if they were formulas. This has the advantage that you now need only one sheet for any calculation with no cross-linking to multiple sheets, making the whole thing easier to comprehend. Another advantage is that we have provided functions with much higher accuracy than the simplified calculations of many of the sections. For example, you can use the method of Section 46 to calculate the Sun's ecliptic longitude approximately, or you can use the function SunLong to calculate it much more precisely.

Let us illustrate the use of functions instead of multiple sheets using the example above. Figure IX shows the spreadsheet of Section 14 using functions instead of multiple sheets. Compare this with Figure VI. You can see that in Figure IX there is now only one sheet, labelled GSTLST.

	A	B	C	D	E	F	G	H	I
1	Conversion of GST to LST								
2									
3	*Input*	**GST hours**	**4**			*Output*	**LST hour**	**0**	=C12
4		**GST mins**	**40**				**LST min**	**24**	=C13
5		**GST secs**	**5.23**				**LST sec**	**5.23**	=C14
6		**geog long**	**-64**						
7									
8	1	GST	4.668119444	=HMSDH(C3,C4,C5)					
9	2	offset	-4.266666667	=C6/15					
10	3	LST (hours)	0.401452778	=C8+C9					
11	4	LST (hours)	0.401452778	=C10-(24*INT(C10/24))					
12	5	LST hour	0	=DHHour(C11)					
13	6	LST min	24	=DHMin(C11)					
14	7	LST sec	5.23	=DHSec(C11)					

Figure IX. Illustrating the use of functions instead of multiple sheets.

The results of the calculation, contained in cells H3, H4 and H5 in both Figures VI and IX, are identical, but in place of the cross-references between sheets at C8, C12, C13 and C14 of Figure VI there are formulas in the corresponding cells of Figure IX. In cell C8, for example, the formula =HMSDH(C3,C4,C5) converts the hours, minutes and seconds (in cells C3, C4 and C5) to decimal hours, with the result shown in cell C8. The contents of C3, C4 and C5 are passed to the function HMSDH as the references contained within the brackets after the function. When the spreadsheet program sees a formula, in this case =HMSDH(C3,C4,C5), it first looks through a list of its own formulas, and then checks to see if the function has been written in BASIC. If it has, the spreadsheet then runs the BASIC program corresponding to the function, passing the contents of the cells in the reference list to the BASIC program, in this case the contents of cells C3, C4 and C5. The result of the calculation is then passed back to the spreadsheet where it appears in the same cell as the function (C8).

Functions like this have been provided for most of the calculations in this book, and are described in the corresponding sections. You will need to download the spreadsheets from the Cambridge University Press website in order to obtain the functions (which are included invisibly with each sheet). Please look in the section “A useful website” on page 209 for details.