CALIBRATION TECHNIQUE FOR ^{14}C DATA CLUSTERS: FITTING RELATIVE CHRONOLOGIES ONTO ABSOLUTE TIME SCALES

HERBERT HAAS

Desert Research Institute, P.O. Box 19040, Las Vegas, Nevada 89132 USA

and

MATTHEW R. DOUBRAVA

University of Nevada, Las Vegas, Department of Anthropology, 4505 South Maryland Parkway, Las Vegas, Nevada 89154 USA

ABSTRACT. Application of radiocarbon dating to a short chronology is often limited by the wide probability ranges of calibrated dates. These wide ranges are caused by multiple intersections of the ^{14}C age with the tree-ring curve. For a single unrelated ^{14}C date, each intersection presents a probable solution. When several dates on different events are available, identification of the most probable solution for each event is possible if one can obtain some information on the relation between these events. We present here a method for such identifications.

To demonstrate the method, we selected a series of ^{14}C dates from mortuary monuments of the Egyptian Old Kingdom. Corrected ^{14}C dates from seven monuments were used. Calibration of these dates produced three absolute ages with single intersections and four ages with 3–5 intersections. These data are compared to a historical chronology, which places the dated events at a younger age. If each intersection is chosen as a potential anchor point of the "correct" chronology, 17 solutions must be tested for the best fit against the historical chronology. The latter is based on the length of the reign of each pharaoh during the studied time span. The spreadsheet has the function of determining the probability of fit for each of the solutions. In a second step the 17 probability values and their offset between the historical and the ^{14}C chronology are graphically analyzed to find the most probable offset. This offset is then applied as a correction to the estimated chronology to obtain an absolute time scale for the dated events.

INTRODUCTION

The availability of precise and detailed tree-ring calibration curves has advanced radiocarbon dating into a more accurate and reliable chronological tool. Numerous publications and several computer programs based on the published data have made the calibration process available to all users willing to acquire the readily available software and obtain basic knowledge from the literature. The Calibration Issues of *Radiocarbon* are a major source for this information (Stuiver and Kra 1986; Stuiver, Long and Kra 1993).

While the accuracy of calibrated dates has increased, the calibration results have become much more complex and difficult to interpret. The user is no longer able to base his conclusions on a point estimate with an associated error. The dating result is given in a range, more likely in multiple ranges from which the user has to select the most appropriate solution. Frequently this is a nearly impossible task. Under certain favorable circumstances, there are methods available to help in the interpretation of the data. The task of interpreting calibrated dates becomes even more complex when numerous dates from a suite of events are available. The technique presented here offers a solution that does not require complex statistical manipulation, yet offers a realistic assessment of the quality of the ^{14}C data. As is the case with all quality assessments, some independent (non-radiometric in this study) information on the chronology must be available.

A Specific Example

From 1985 to 1987 a ^{14}C dating project on Old Kingdom monuments in Egypt was sponsored by the American Research Center in Egypt (ARCE) (Haas *et al.* 1987). Dated were charcoal, wood and straw samples from pyramids and mortuary temples. ^{14}C dates from the same monument were averaged and then calibrated with a calibration program developed by S. Robinson (Hassan and Robinson 1987). The calibration results obtained were the centroid values of the probability curve obtained from the intersection of the ^{14}C date (as a Poisson probability distribution) with the calibration curve and its respective error distribution. These centroid values allowed a simple comparison of the ^{14}C dates with the historically based chronology (Edwards 1985). The surprising result was an average increase of the ^{14}C ages for the 17 dated monuments by 375 yr over the historically constructed ages.

Because the calibration curve is nonlinear, calibrated ages cannot be precisely stated as a most probable result with an associated error range (van der Plicht 1993). The availability of more sophisticated calibration methods and computer software led to the decision to recalibrate the 1985 data. The CalibETH program was used (Niklaus 1991), which provides probability ranges and exact curve intersection values. Most of these ^{14}C dates fell in the range of 4500 to 3500 BP. An inspection of the calibration curve in this range reveals the presence of five flat segments in the curve, which produced multiple probability ranges from which a straightforward comparison of the ^{14}C and historical chronologies was no longer possible. Figure 1 shows an especially broad range of multiple intersections. Among these, only one represents the true age. The process of identifying this intersection can be quite overwhelming when the chronology includes ten or more dated events that all need to be considered to find the correct calibrated age for each event. The spreadsheet process presented here performs many of the lengthy computations automatically while presenting graphic displays for visual evaluation of the process.

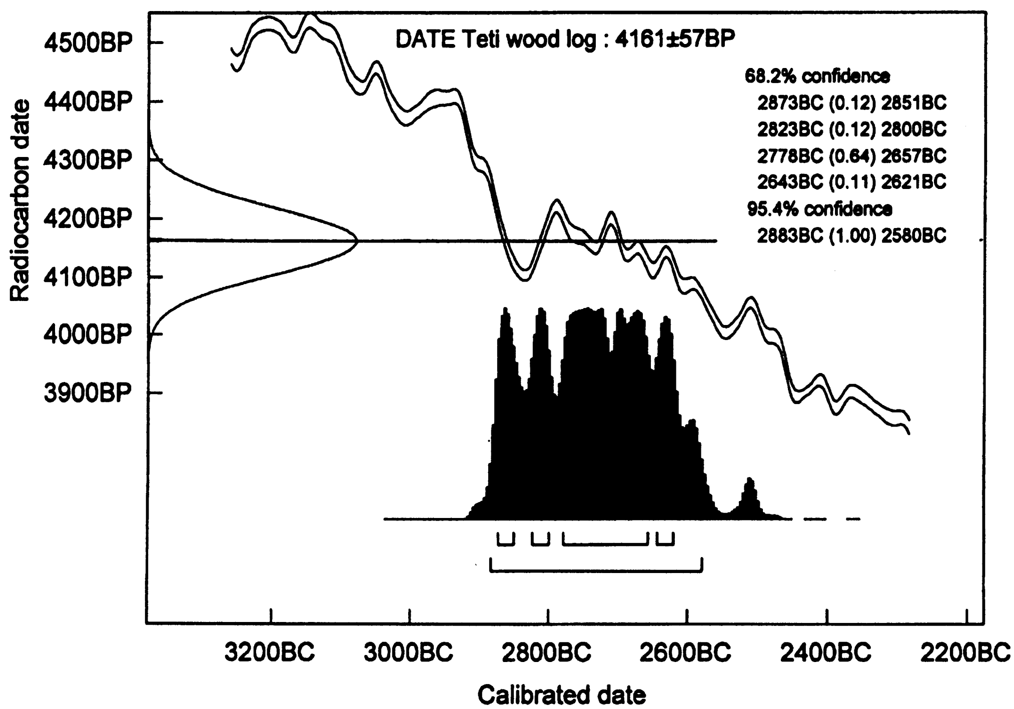

Fig. 1. ^{14}C date intersecting a flat portion of the calibration curve, producing 5 intersections and a 252-yr wide probability distribution with a 1-σ confidence level

Introducing the Intersection Method

The process starts with a set of calibrated dates. Identification of the range that best represents the true age among multiple ranges is not possible without additional information on the chronology. In a situation where the intervals between several geological or archaeological episodes are known, or can be estimated, the proposed intersection-matching technique can be applied. This matching technique is a three-step procedure:

1. An estimation of the probable chronology is recorded in the first of two spreadsheets, using all available information other than radiometric data and thriving to get good estimates on the duration or the time separation of the dated events.
2. Using calibration results, the difference between the estimated chronology and the radiometric data is evaluated and a number of possible corrections (called "discrepancy" in the following explanations) to the estimated chronology is derived by the spreadsheet's computations.
3. The most probable value of these corrections is established by the second spreadsheet and its graphic plots. This correction is then applied to the initial, estimated chronology in order to place it correctly in the absolute time scale.

Figure 2 illustrates this process, leading to a chronology on the absolute time scale, which determines the most probable age for each event. The actual computation is a multi-staged process. The ideal tool for performing the task is a spreadsheet with graphics display capabilities.

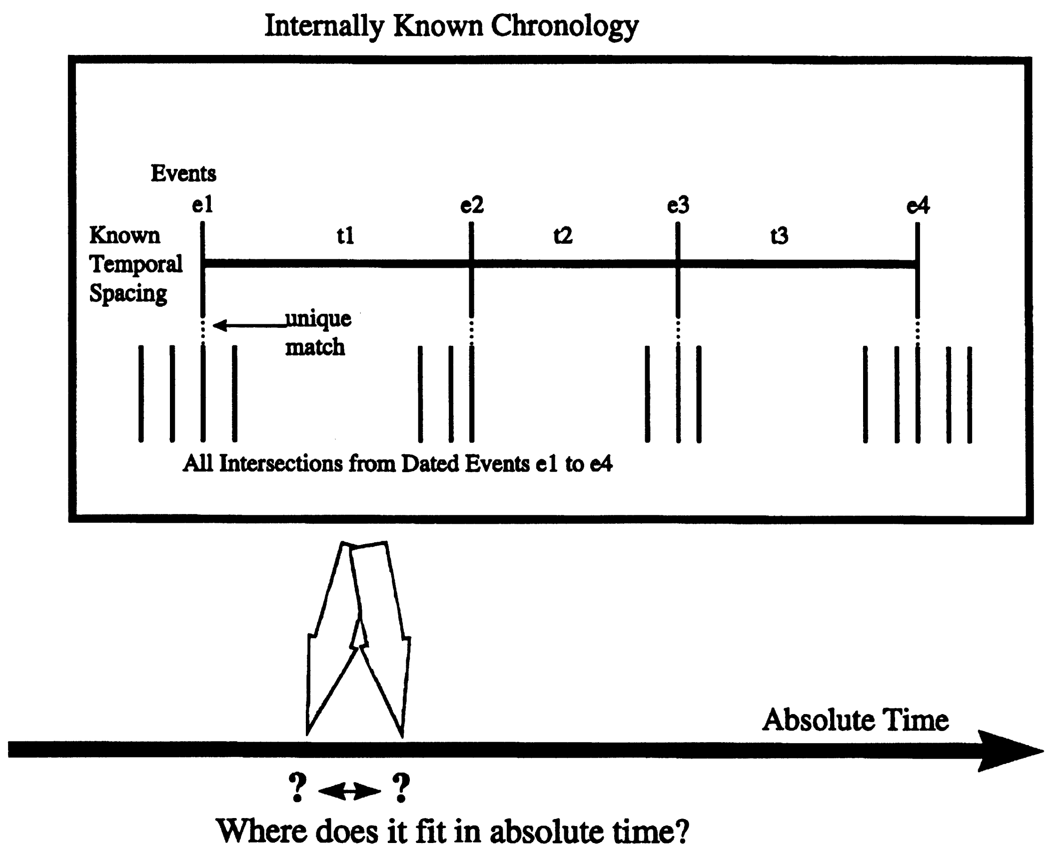

Fig. 2. A hypothetical chronology of four events points to matching inter-sections from four calibrated dates

Definition of Terms

We will consistently use these terms and definitions in the following description of the spreadsheet design:

Historic chronology: Information on the ages of a series of episodes, based on written, lithic or other, non-radiometric information.

Episode: A phenomenon of interest for which there is estimated or precise time information on the *historic* time scale.

Interval: Time span between two episodes.

^{14}C age: Age calculated with the Libby half-life (5568 yr) from measured ^{14}C activity relative to standardized activity of oxalic acid, corrected for isotope fractionation and listed in years "before present" (BP).

Radiocarbon chronology: A series of calibrated dates, each related to a specific event or monument.

cal age: A calibrated ^{14}C age date relating to a specific event or monument. As a result of the calibration process, multiple answers are possible, each originating from an intersection with the tree-ring calibration curve.

Intersection: An age derived from a "before present" (BP) ^{14}C age intersecting the calibration curve. Multiple intersections result from wiggles in the curve.

Anchor point: Selecting a listed intersection as the true age of an event, against which all other data from events and episodes are compared and evaluated by the "sum of differences". During a thorough evaluation of the ^{14}C chronology, most intersections are successively chosen as anchor points.

Event: A phenomenon of interest for which a cal age is available. It is the equivalent to *episode* in the historic time scale. Also, the difference between event and episode represents the *discrepancy* between the historic and the radiocarbon chronologies for that particular phenomenon.

Discrepancy: Separation in age of the same phenomenon in the historic and the ^{14}C chronologies. Because of multiple intersections, several cal age values are possible and consequently a corresponding number of discrete values for the discrepancy must be considered.
Note: In this definition, the cal age is directly derived from the ^{14}C measurement on the phenomenon. In contrast, the term *difference* will be used in connection with computed ages.

Difference: Comparison of the cal age of an event with the interval adjusted cal age of another event in the chronology. Interval adjustment is accomplished by adding or subtracting the historic chronological time separation to the second event in order to shift it to the same chronological time of the first event for the purpose of comparison. This comparison serves as test of adequacy of the ^{14}C chronology. The *difference* may have a positive or negative value.

Sum of differences: The process of computing the difference between two events is repeated until all differences between a selected event and every other event in the chronology are computed. These differences are summed including their signs. The smallest sum of differences will identify the ^{14}C chronology that is closest in agreement to the intervals between episodes defined by the historic chronology.

Description of the Spreadsheet

Below is a step-by-step demonstration of the procedure. The set of dates from the 1985 sampling of the Old Kingdom monuments in Lower Egypt is used to show the procedures. The data input requires the following columns:

- Listing of episodes that are being dated (the Pharaohs' reigns).
- Independent chronological information available for the episodes, which in this case is the terminal year for the reigns (Clayton 1994).
- The duration of each episode, calculated from the previous column
- ^{14}C dates from several episodes, listing the observed intersections with the curve in separate columns. A practical maximum number of listed intersections is five per dated event.

Additional columns contain the computations and results. The headings of all discussed columns and a few lines of data are shown in Figure 3. We will discuss only three computational columns of importance.

OLD KINGDOM CHRONOLOGY, YEARS BC

active anchor point >> **2872**
offset betw. historical and computed chronology 223

Episode	historical chronology BC	length of episode in years	Calibrated age of event <<<<<<<<I N T E R S E C T I O N S>>>>>>>>>					anchor points interval adjusted to first episode	computed age of each event relative to the active anchor point	differences between computed age and cal age
DJOSER	2649	19	$\boxed{2868}$	2805	***2770***	2719	2703	***2770***	2872	-4
SEKHEMKHET	2643	6	***2866***	2808	2757	2722	2700	***2872***	2866	0
KHABA	2637	6	not dated						2860	
HUNI pyramid	2613	24	$\boxed{2836}$	***2829***	2618			***2836***	2836	0
SNEFRU	2589	24	***2864***	$\boxed{2821}$	2661	2637	2626	***2914***	2812	9
										5

interval — selected anchor points — $\boxed{nnnn}$ closest matching intersections — sum of differences

Fig. 3. Heading of the spreadsheet with five lines of data. The bold intersection of 2866 serves as anchor point of a trial chronology. From this date an age was computed for the first event (Djoser) at 2872 BC and a nearly matching intersection (2868 BC) was identified, with a difference of −4 yr.

In an unbiased approach, every intersection listed is used as an anchor point. In a more practical approach, events with single intersections are evaluated first, followed by events with smaller numbers of intersections.

1. Select an anchor point.
2. Using intervals, compute the age of every event in the chronology. Take special note of the computed age of the first event in the chronology.
3. Compare the computed ages of each event with its set of intersections, find the closest matching intersection and calculate the difference to the computed age. Store this difference in a column and include the plus or minus sign.
4. Compute the sum of the differences and store it together with the age of the first event for use in the second spreadsheet. Figures 4 and 5 show bar graphs of the differences.
5. Take the age of the first event, computed in step 2, and establish the discrepancy to the age of the first episode in the historic chronology. In an x-y plot, mark this discrepancy on the horizontal axis. Plot the "sum of differences" on the vertical axis. Figures 6 and 7 are examples of this plot.

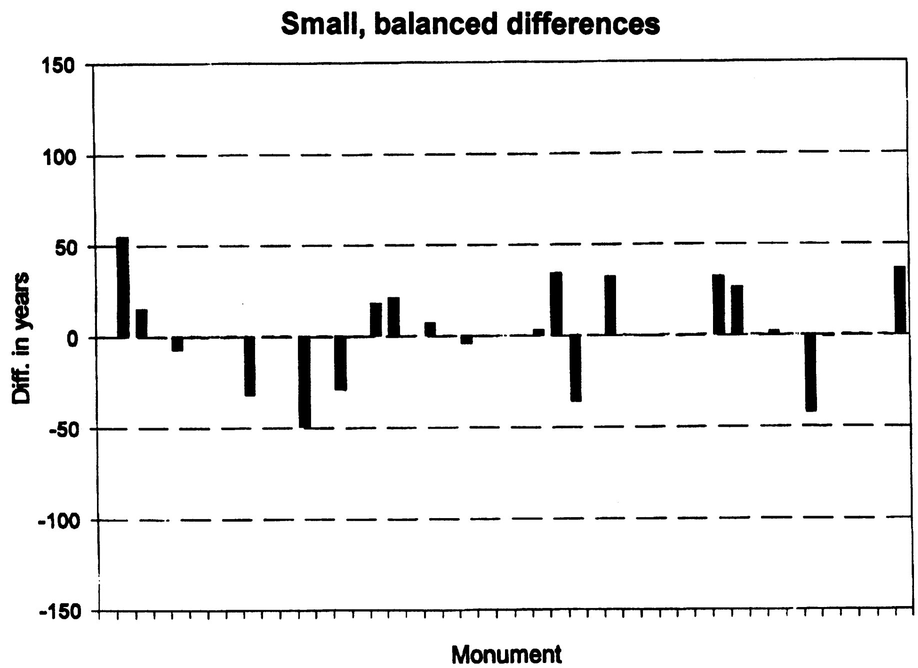

Fig. 4. A balanced set of differences between computed and calibrated ages

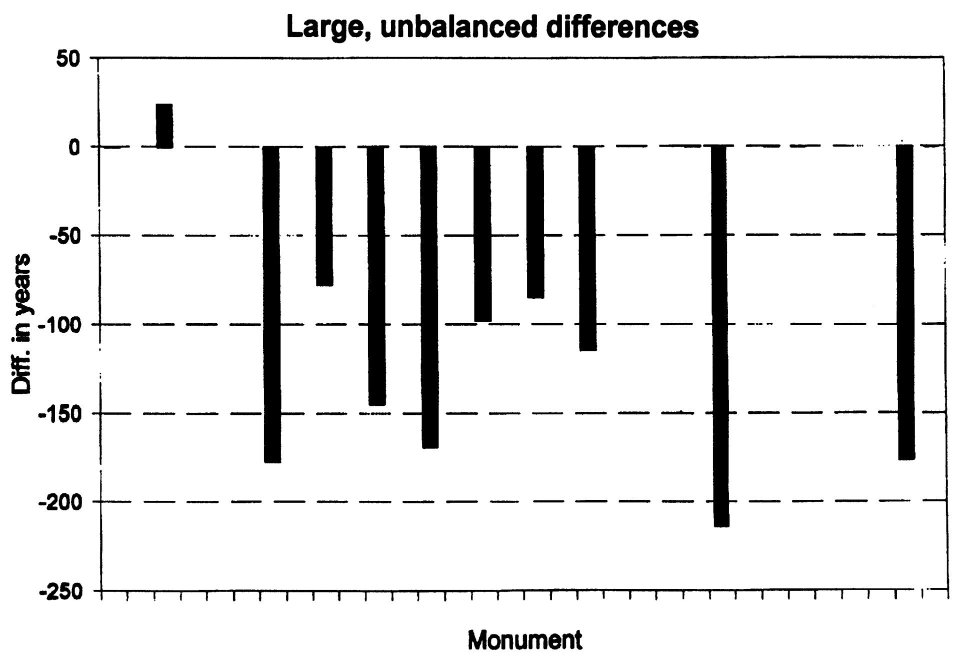

Fig. 5. With one exception all differences are large and in the same direction, indicating that the chosen anchor date is not matching the hypothetical chronology

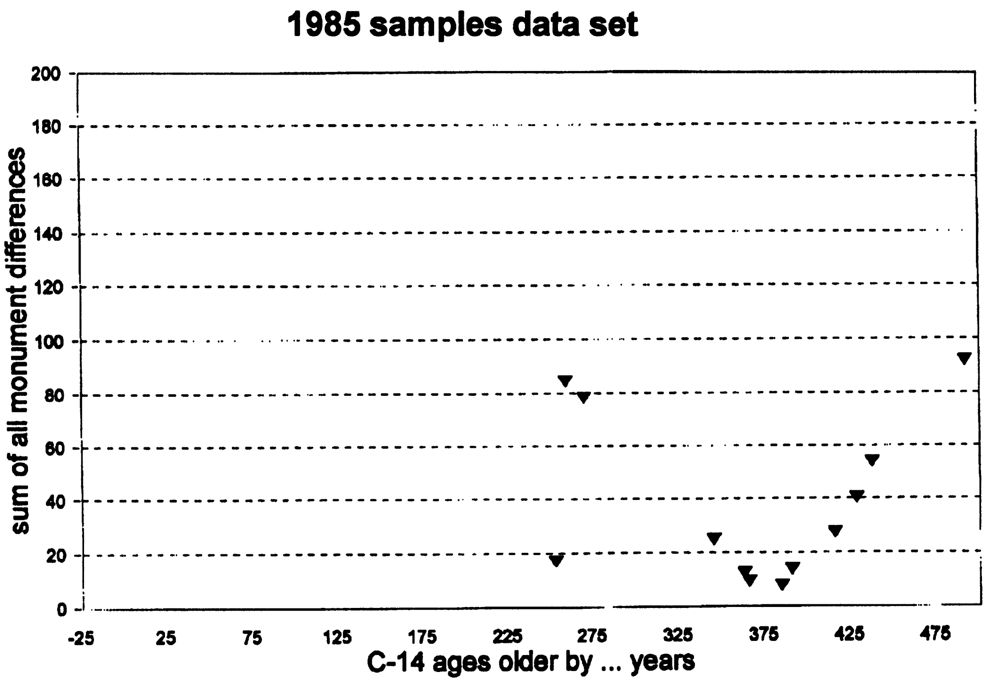

Fig. 6. Distinct minimum of the sums of differences, showing a well-defined offset of the ^{14}C chronology from the hypothetical chronology, amounting to 375 yr

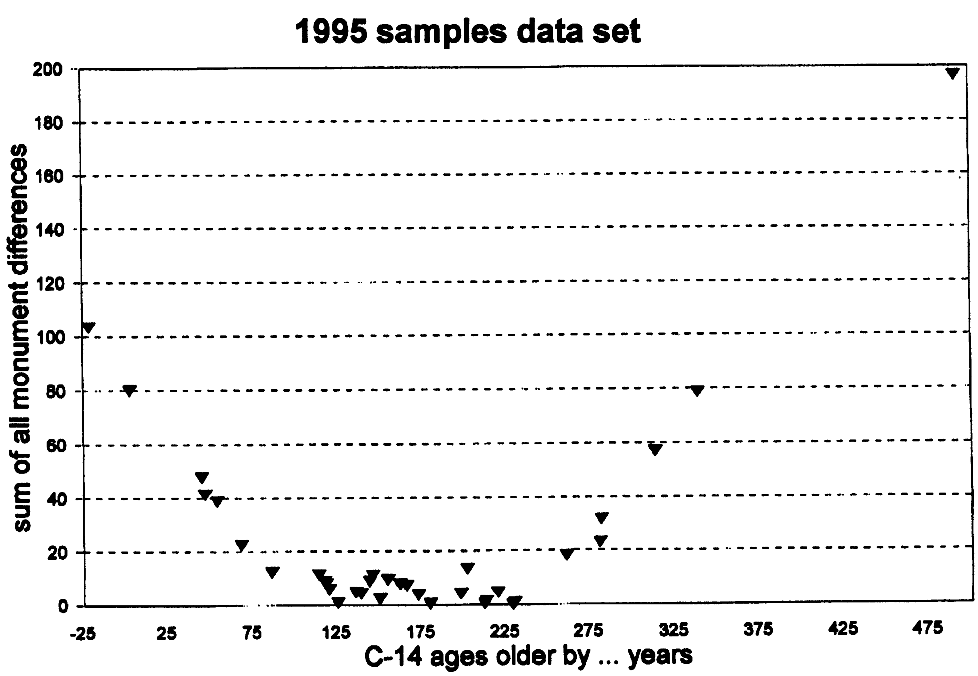

Fig. 7. The sums of differences are low over a 100-yr-wide minimum, indicating a mismatch in the spacing of events (intervals) between the historical and ^{14}C chronologies.

Practical Methods for Using the Spreadsheet

Anchor points are selected one at a time and are set in the spreadsheet in one cell location near the title rows. From there the necessary computations are initiated automatically with cell references. This avoids a need to make changes in the spreadsheet itself. Each change to the anchor point creates a new set of differences for which a bar graph should be printed and the sum of differences recorded. Large differences are omitted in the "sum of differences" computation and in the graph. The threshold for omission can be adjusted; in our Old Kingdom example, we choose 180 yr. This step avoids the effect of outlier intersections, which usually have a small statistical weight, and improves the visual interpretation of small differences in the graphs. The tabulation of the "sums of differences" and discrepancy values was performed with an independent new spreadsheet from which the final interpretative x-y graph was created.

Discussion and Conclusion

The sum of differences is a sensitive measurement for the match between the estimated or historical chronology and the radiometric data. In the current demonstration based on samples collected in 1985 from Old Kingdom monuments and shown in Figure 6, sums of differences become very small (<10 yr) and point in a sharp "V" configuration to a discrepancy of 365–387 yr. In Haas *et al.* (1987), the average chronological difference between historical and radiometric data was 374 yr.

The spreadsheet method was further tested with a different set of samples taken in 1995 from Old Kingdom monuments (Fig. 7). It shows a generally smaller discrepancy of 125–230 yr, but more characteristically, a much broader range of low "sum of differences" values. This suggests a lower internal consistency of the data set and confirms the observation that individually dated samples from most monuments have a wider age spread than similar sample sets in the first example. The conclusion then is that the presented spreadsheet method not only yields a numerical value for the discrepancy between historical and ^{14}C chronologies, but also offers a qualitative assessment of the internal consistency of the data. It does not provide, however, a numerical value for the error since it is not based on traditional statistical methods.

To test the sensitivity to the internal consistency of the ^{14}C dates, changes were made to the historic chronology in the 1985 example. The ages of several monuments were changed by 10–20 yr. As expected, the discrepancy also changed, but the pointed "V"-shaped pattern of the sums of differences remained unchanged.

Application of this method is restricted to archaeological or geological site studies where independent chronological data are already available and need to be tested. In archaeological sites, the independent data are based most likely on lithic or ceramic typology or inscriptions.

Acknowledgments

^{14}C dates used in this study were measured at the ETH AMS laboratory in Zürich, Switzerland, the former SMU laboratory in Dallas, Texas and the DRI laboratory. Samples were collected by Mark Lehner, Robert Wenke, John S. Nolan and Herbert Haas. Research was supported by the American Research Center in Egypt and by the David Koch Foundation.

References

Clayton, P. A. 1994 *Chronicle of the Pharaohs*. London, Thames and Hudson Ltd.: 224 p.

Edwards, I. E. S. 1985 *The Pyramids of Egypt*. Harmondsworth, England, Viking: 328 p.

Haas, H., Devine, J., Wenke, R., Lehner, M., Wölfli, W. and Bonani, G. 1987 Radiocarbon chronology and the historical calendar in Egypt. *In* O. Aurenche, J. Evin and F. Hours, eds. Chronologies in the Near East. *BAR International Series* 379: 585–606.

Hassan, F. A. and Robinson, S. W. 1987 High-precision radiocarbon chronometry of ancient Egypt, and comparisons with Nubia, Palestine and Mesopotamia. *Antiquity* 61: 119–135.

Niklaus, T. R. 1991 *CalibETH, User's Manual*. Zürich, Reprozentrale ETH Hönggerberg: 151 p.

Stuiver, M. and Kra, R. S., eds. 1986 Proceedings of the 12th International ^{14}C Conference, Calibration Issue. *Radiocarbon* 28(2B).

Stuiver, M., Long, A. and Kra, R. S., eds. 1993 Calibration 1993. *Radiocarbon* 35(1): 1–244.

van der Plicht, J. 1993 The Groningen radiocarbon calibration program. *In* Stuiver, M., Long, A. and Kra, R. S., eds., Calibration 1993. *Radiocarbon* 35(1): 231–237.