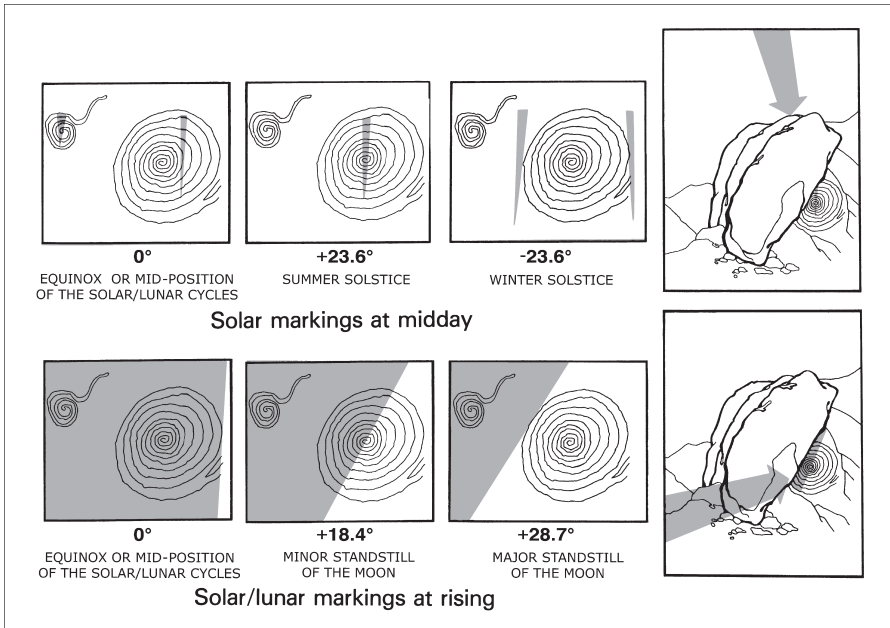

The Sun Dagger Interactive Computer Graphics Model

A DIGITAL RESTORATION OF A CHACOAN CALENDRIAL SITE

In 2006 an interdisciplinary team, coordinated by the Solstice Project,¹ produced an interactive computer graphics model that precisely replicates the astronomical functioning of an ancient calendrical site, the Sun Dagger, of Chaco Canyon, New Mexico. The interactive, three-dimensional format of this digital model provides opportunities for extensive research of the structure's light patterns, as well as its geometry and the process of its original development.

At the Sun Dagger site, which Anna Sofaer rediscovered in 1977, three upright sandstone slabs cast precise light and shadow patterns on two spiral petroglyphs, recording the summer and winter solstices, the equinoxes, and the 18.6-year lunar cycle (Sinclair et al. 1987; Sofaer and Sinclair 1987; Sofaer, Sinclair, and Doggett 1982; Sofaer, Zinser, and Sinclair 1979; figures 3.1–3.4).² This site is located on a southeastern-facing cliff near the top of the 135-m-high Fajada Butte, which stands prominently at the south entrance of Chaco Canyon.

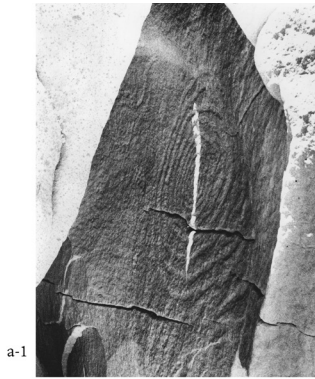
The rediscovery of the Sun Dagger site was followed by intense visitation. This activity caused acceleration of the process of natural erosion at the site, which, in turn, caused significant shifts in the positions of the slabs and the light markings. Thus the precise archival replication of the Sun Dagger site allows appreciation and study of its astronomical functioning that can no longer be observed or recorded.



3.1. Diagram of solar and lunar markings of the Sun Dagger site as originally recorded, showing how the light comes onto the spirals from the sun's passage above the slabs and from the sun's and moon's rising positions. © Solstice Project.

In addition, this effort succeeded in its goal to present as clearly as possible for potential researchers—with no “agenda” of interpretations—a model that accurately replicates the physical elements of the Sun Dagger site in comprehensive detail. Thus, with precise astronomical orientation and programming also incorporated in the model, users can experiment with the interplay of these elements with the cyclical movements of the solar and lunar cycles and evaluate the shifting patterns of shadow and light for their significance as markings. In other words, this model allows and invites people to develop their own interpretations of the site without the bias of former interpretations. The implication of this effort for archaeological studies is that models of sites—whether on this small scale or of larger structures, such as buildings and roads, that simply present comprehensive data in three-dimensional and interactive formats—can facilitate unbiased research opportunities, as well as archival restoration.

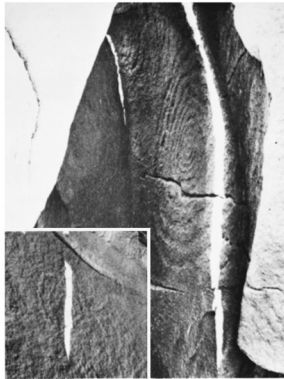
This chapter first discusses the larger context of the Chacoans' extensive expression of astronomy and cosmography, in which the Sun Dagger site is one part. In this context the Pueblo associations with the sacred nature of the site are reported. The site itself is then described in detail: its solar and light markings and



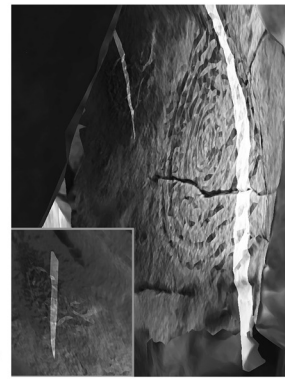
a-1



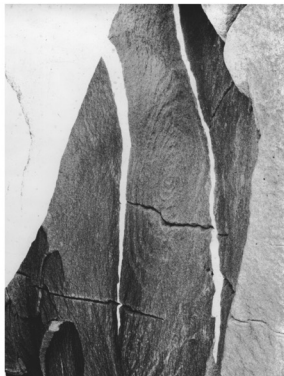
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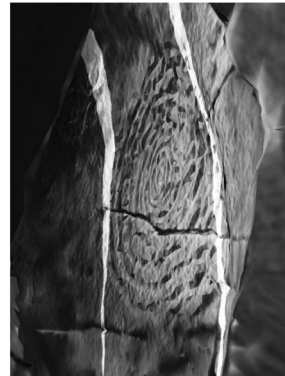
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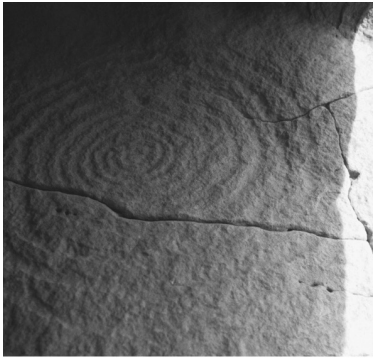


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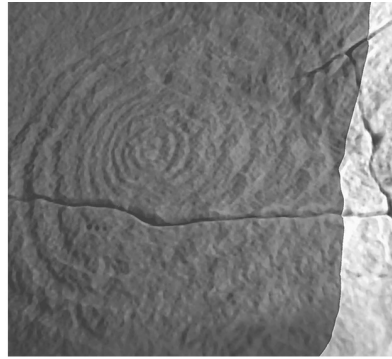


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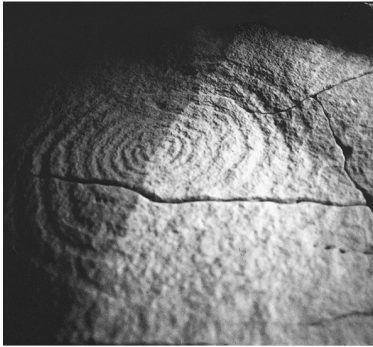
3.2. Pairs of 1978 photographed images and 2006 registered model simulated images: a, summer solstice (June 26, 1978, 11:13:15 AM Local Apparent Time [LAT]); b, equinox (September 21, 1978, 10:50 AM [LAT]; insert 10:52 AM [LAT], not noted in Sofaer, Zinser, and Sinclair 1979); c, winter solstice (December 22, 1978, 10:22:15 AM [LAT], corrected from Sofaer, Zinser, and Sinclair 1979). (The correction noted here from Sofaer, Zinser, and Sinclair 1979 is based on an error recently identified in the original reading of the winter solstice 1978 photographic contact sheets and log.) In each pair, the exact time of the 1978 recorded photo was used in the simulation. Photos by Karl Kernberger (1978); simulated images by Alan Price (2006). © Solstice Project.



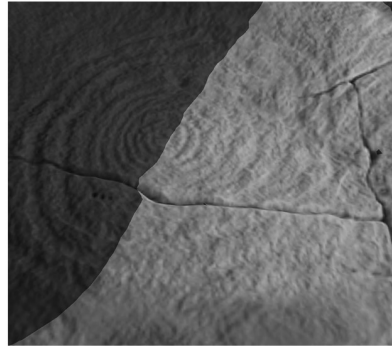
a-1



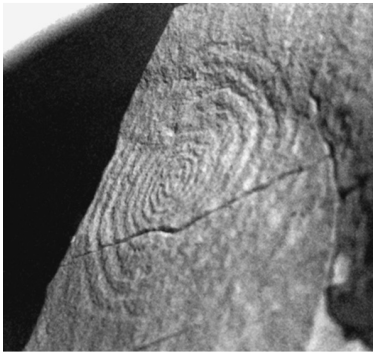
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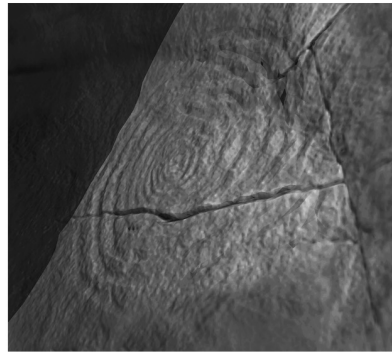
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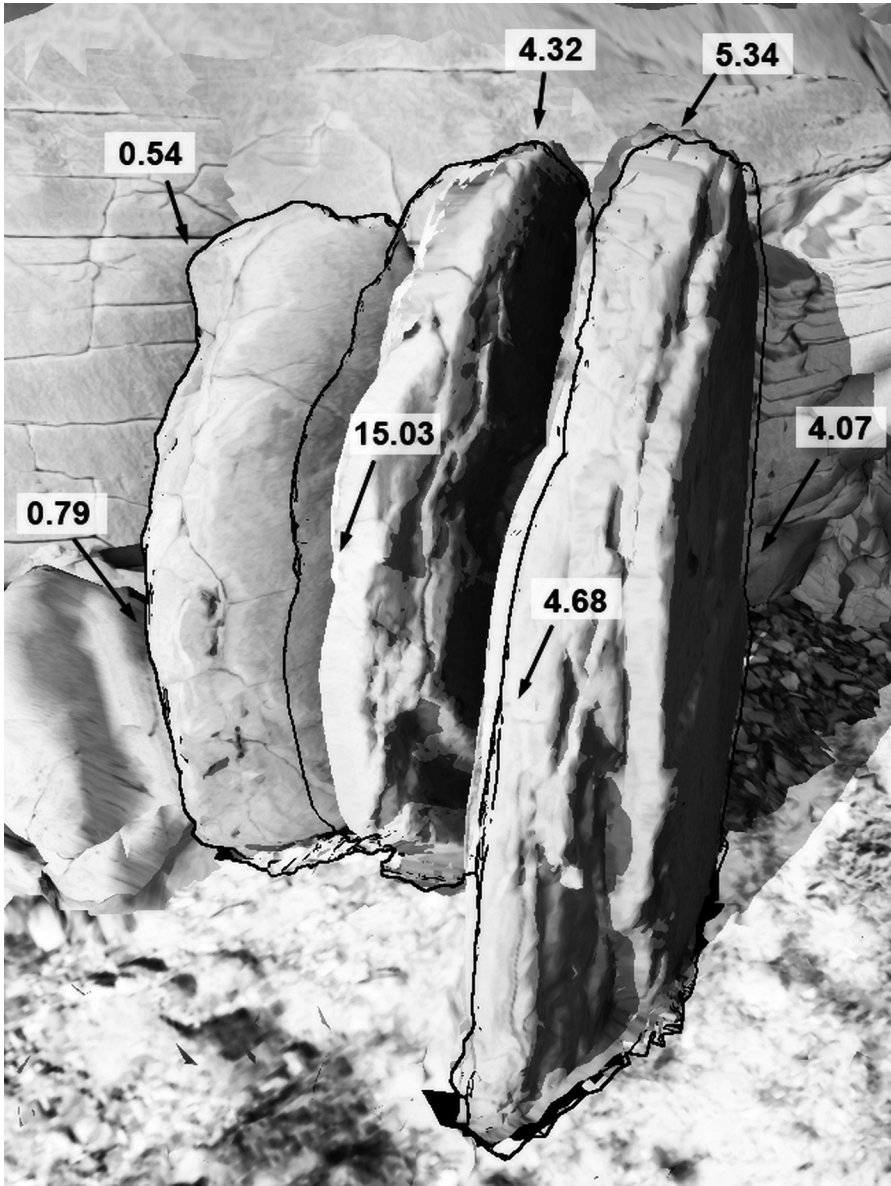


c-1



c-2

3.3. Pairs of 1980 to 1987 photographs with 2006 registered model simulated images of rising sun and moon markings: a, equinox (September 23, 1980, sunrise at approximate azimuth 90.2 degrees); b, northern minor lunar standstill (May 13, 1980, using the sunrise to simulate the moon at approximate azimuth 67.4 degrees); c, northern major lunar standstill (November 8, 1987, moonrise at approximate azimuth 55.4 degrees). In each pair, the dates of the photographs are used in the simulations. The altitudes of the high edge of the disc of the rising sun or moon are taken in the simulations as 0.35 degrees above the true horizon of 0.2 degrees. Photos by Karl Kernberger (1978), Nevada Weir (1980), and Rolf Sinclair (1987); simulated images by Alan Price (2006). © Solstice Project.



3.4. The slabs in an image developed from the registered model and the laser-scanned model that show their original positions, outlines of their disturbed (2005) positions, and measurements of some of the differences between the 2005 and 1984 positions. Simulated image by Alan Price. © Solstice Project.

its shadow-casting features. The chapter reports the deterioration of the site caused by excessive visitation following its rediscovery. The process of the digital restoration of the site is fully explained, including an integrated use of photogrammetry and laser scanning. Finally, the chapter reports on the interactive tools developed for the model to facilitate open-ended research on the site's astronomical functioning and its original development.

THE SUN DAGGER SITE: ONE PART OF CHACOANS' ASTRONOMY AND COSMOGRAPHY

The Chaco culture redundantly expressed the integration of the solar and lunar cycles, often in relationship to key features of the Chacoan landscape. As other chapters in this volume note, distinctive landscape features probably played an important role in Chacoans' decisions to locate cosmologically significant sites (chapter 1), and artifact resource locations may have been imbued with special meanings (chapter 2). Astronomical knowledge and expression appear to have formed a unifying cosmology for Chacoan people across the vast region of their culture. This cultural florescence was centered in Chaco Canyon, itself a topographic center in an open and spare landscape.

Research by the Solstice Project has shown that twelve of the Chacoans' major buildings—eight in Chaco Canyon and the four largest outlying buildings—are oriented to the solar and lunar cycles (Sofaer 2007). These orientations are to the azimuths of the extremes and mid-positions of the sun and moon marked at the Sun Dagger site and at two other sites on Fajada Butte (Sofaer and Sinclair 1987). The inter-building alignments and internal geometries of the Chacoans' major buildings also express solar and lunar relationships (Sofaer 2007). The inter-building alignments form an astronomical regional pattern of approximately 5,000 square kilometers. This pattern was centered and cardinally organized at the central complex of Chaco Canyon. In addition, one of the primary Chacoan roads, the Great North Road, appears to have been built to commemorate the relationship of the central complex of Chaco Canyon to celestial north and to a badlands canyon in the north (Sofaer, Marshall, and Sinclair 1989).

The Chacoan people integrated their knowledge of astronomy with the use of visually prominent—and sometimes dramatically situated—features of the landscape. The extensive solar and lunar patterning of the Chaco architecture is symmetrically ordered and centered in the most sharply defined topography of Chaco Canyon. Pueblo Bonito (PB) and Chetro Ketl (CK), the two largest buildings of the Chaco world, are east-west of each other: they are located at the base of the cliffs that rise most precipitously from the canyon floor. Pueblo Alto and Tsin Kletsin are north-south of each other, forming a north-south axis that divides the east-west

distance between PB and CK: they are located on two of the most elevated sites of the Chaco mesas. The Great North Road is an elaborate construction that runs 50 km to the north from this central complex—across an open plain—and descends the steepest slope of a badlands canyon in the north, where above this slope a prominent feature is located. The light markings atop Fajada Butte also appear to be a cosmographic expression—their occurrence at high sites was chosen perhaps for its relationship to “the world above.”

Members of today’s Pueblo communities, descendants of the Chacoan culture, have expressed their regard for the Sun Dagger as a sacred site, also noting its dramatically elevated location. The late Alfonso Ortiz (anthropologist and member of the Pueblo, Ohkay Owingeh) said that the Sun Dagger site “would be one of the central concerns of their [the Chacoans’] lives and there would be people there on a regular basis praying, meditating, leaving offerings, and making observations” (Solstice Project 1982). Ortiz further noted the Puebloan character of the Sun Dagger site as “a center of time on a high butte.”

As Ortiz considered photographs of the solar markings at the site in 1978, just prior to the Solstice Project’s finding of lunar markings there, he perceived that “where the sun is so marked, so would be the moon” (Solstice Project 1982). He believed this, he said, because in the Pueblos’ traditions the sun and the moon are held as spiritual beings who reside in complementary relationships with each other. He also noted that one or two people would be at the Sun Dagger site observing the light markings and that their observations would determine the beginnings and endings of ceremonies in the canyon. These comments anticipated what research would show to be true in the coming years.

Chacoan people, with very different kinds of experiences, appear to have been united in a shared attention to celestial cycles. The intimate observations of the Sun Dagger site by a few ceremonial officiants, suggested by Ortiz, contrast with the large public settings of the massive Chaco buildings and great kivas where vast numbers of people probably participated in ritual acts related to the sun and moon. Yet while viewing the sun’s and moon’s alignments or markings, whether at the Sun Dagger site or at a Chaco building, on a day of equinox or solstice or a night of the lunar standstills, they were within the same experience of cosmology.

In some instances Chacoans observing the same astronomical phenomenon would be at sites great distances from each other. As an example, at Chimney Rock Pueblo, a Chacoan building set on a precipice in southwestern Colorado, people would have the spectacular view of the moon rising between two pillars of rock at its northernmost position in its 18.6 standstill cycle, the northern major standstill (Malville and Putnam 1989); at that same time, ceremonial officiants would see the moon’s shadow mark the large spiral petroglyph on Fajada Butte. These sites are separated by 140 km.

Some have suggested that the dispersed Chacoan communities, located across the 80 or more square kilometers of the Chaco cultural region, were related to each other—and sometimes joined in pilgrimage to the ritual buildings of Chaco Canyon—by a precisely timed solar and lunar calendar (Judge and Malville 2004). This calendrical knowledge was probably held as sacred—and its details maintained secretly in esoteric contexts—to be experienced by some in small private events and by others in large-scale public hierophanies.

All participants must have had some experience or perception of Chaco Canyon as a center of significant power, where cosmological knowledge was expressed most intensely. Paul Pino of Laguna Pueblo conveyed that Ancestral Pueblo history may have carried such an understanding of Chaco: “In our history they talk of things that occurred a long time ago, of people who had enormous power, spiritual power, and power over people. I think those kinds of people lived here in Chaco” (Solstice Project 2000).

THE SUN DAGGER SITE

Near the top of the 135-m-high Fajada Butte at the south entrance of Chaco Canyon, three sandstone slabs lean against a southeast-facing cliff (figures 3.1, 3.4). Each measures 2 to 3 m high and weighs from two-thirds to one and a third tons. The openings between the slabs are to the south-southeast. Of the two spiral petroglyphs pecked into the rock face behind the slabs, one, 41 cm across, has nine and a half turns; the second, to its left and 13 cm across, has two and a half turns.

Solar Light Patterns

The slabs cast vertical light patterns onto the cliff each day in the late morning to near solar noon. These patterns form markings on the two spirals that are distinctive to the solstices and equinoxes. At summer solstice the opening between the middle and eastern slabs forms a slim dagger of light. It begins forty-seven minutes before solar noon in the top turn of the large spiral as a small spot of light that lengthens to a dagger shape bisecting the spiral. It descends through and off the spiral eighteen minutes after its first appearance. Four days before or after the summer solstice, a slight rightward shift of the light dagger—of about 2 mm—occurs in its position in relation to the center of the large spiral. In four weeks it is 3.2 cm to the right of the center. Through the following weeks and months, the light dagger descends through the spiral in positions farther and farther to the right.

Soon after the summer solstice a second light dagger, formed by the opening between the middle and western slabs, joins the first. It also descends in a vertical

course along the cliff face each day and moves farther to the right as the seasons progress. The second light dagger bisects the small spiral at equinox one hour and ten minutes before solar noon.

At the winter solstice the two vertical light daggers descend over the course of three hours. When the second dagger matches the first in length, one hour and forty-one minutes before solar noon, both are on the outer edges of the large spiral. At this time of the sun's lowest passage, the light daggers appear to frame the spiral—bisected by the sun during its highest passage, at summer solstice—now empty of light.

Lunar and Equinox Light Pattern

The eastern slab creates shadow patterns that record the extremes of the moon in its 18.6-year cycle—the northern major and minor lunar standstill positions—and the equinox, or the mid-position of the sun or moon. The inner (or northern) edge of the eastern slab casts a shadow on or adjacent to the large spiral as the sun rises or the moon rises (during phases of its nighttime rise) at azimuths between approximately 54 and 90 degrees. In the year of the major lunar standstill, when the moon rises at its northernmost position in its 18.6-year cycle at an azimuth close to 54.3 degrees, the eastern slab casts a shadow tangent to the left edge of the large spiral. Nine and a third years later, when the moon rises at its northern minor standstill position at an azimuth close to 67.1 degrees, a shadow from this same slab diagonally bisects the large spiral. Twice yearly at the equinox, when the sun rises—or when the moon at the mid-position of its cycle rises—directly east (close to 90 degrees), the same slab casts a shadow onto the right edge of the large spiral.³

It appears that the Chacoans gave distinctive emphasis to the lunar patterns by their alignment of two pecked grooves with the shadows of the minor and major standstill moons (Sofaer and Sinclair 1987:figure 4.3; figure 3.3b in this chapter). It is also of interest that the ten turns of the left side of the spiral that the shadows cross, year by year, during the progression of the moon from its northern minor to its northern major standstill correspond closely to the nine-and-one-third years of this journey by the moon. In addition, the nineteen turns of the spiral from its left to right edges may symbolize the full lunar standstill cycle of 18.6 years.

In sum, the three large sandstone slabs at the Sun Dagger site mark the extremes and mid-positions of both the solar and lunar cycles on the same large spiral and the equinox on the smaller spiral as well. The site reveals significant coordination in the markings. The Chacoans created solar and lunar markings that repeatedly fall on the center and outer edges of the large spiral. These findings raise a number of intriguing research questions. How sensitive (not critical)

are the relationships of the slabs' positions and shapes to these light and shadow formations? What activities and process did the Chacoans conduct at the site? How might they have placed and shaped the spirals and the cliff face on which they are carved and shaped the slabs and adjusted their positions to achieve their results?⁴

During the ten years following Sofaer's 1977 finding, the Solstice Project collected timed photographic records of the light and shadow formations of the Sun Dagger site. In 1989 the project discovered that disturbances at the site had destroyed its solar marking functions. Largely because of the site's attractiveness to tourists and investigators, the middle of the three slabs had pivoted 2 to 5 cm from its originally recorded position (Palca 1989; Sofaer and Sinclair 1990; Trott et al. 1989).

In 2005, combining state-of-the-art Global Positioning System (GPS) and 3D Light Detection and Ranging (LiDAR) techniques with photogrammetric measurements collected in 1984, a team that included an archaeoastronomer, a geodesist, a computer graphics specialist, and several mapping specialists produced two high-resolution 3D computer models of the 1984 and 2005 positions of the slabs (Nicoli et al. 2006). Integration of these models produced a virtual restoration of the site that simulates the original interaction of sunlight and moonlight with the slabs and petroglyphs. This virtual restoration serves as an archival record of the site, an interactive research tool, and an educational resource.

DEVELOPING AN ARCHIVAL RECORD _____

Beginning in 1978, the Solstice Project set out to develop an archival record of the Sun Dagger site and envisioned a three-dimensional computer graphics model for research. In fact, a quarter of a century would pass before the technology existed to accurately replicate the site in such a model. Yet early on, the Project recognized that beyond providing an archival record of the fragile site, a 3D computer graphics model would allow interactive experiments to further test the sensitivity of the site's geometry to the positions of the sun and the moon. These experiments, in turn, would give modern researchers the chance to gain insights into the process and concepts behind the Sun Dagger's original development.

Early Efforts

Between 1978 and 1987, the Solstice Project collected comprehensive, timed photographic records of the light and shadow formations of the Sun Dagger site.

The Project first contracted photographer Karl Kernberger to record the light patterns on the spiral petroglyphs in an extensive series of precisely timed images.

Near the twenty-first of each month of the 1978 solar cycle, he used a Hasselblad camera with a 50 mm lens to photograph from a single position, every thirty seconds, the changing light patterns through their duration.

In 1980 the Solstice Project photographed the lunar standstill markings on the spirals, using the sun to simulate the rising minor standstill moon's shadow and a laser to simulate the rising major moon's shadow seven years before it reached its major standstill position. In 1987, when the moon had reached this position, the project photographed the moon's shadow cast by the eastern slab (Sinclair et al. 1987; see figure 3.3c[1], this chapter). Between 1979 and 1987 the Project also collected time-lapse images with 16 mm film of the light patterns on the spirals at the solstices and the equinox. In addition, it recorded extensive measurements and documentation of other shadow and light formations on the spirals and identified the shadow-casting edges of the rock slabs.

Because of the extreme fragility of the site's soft sandstone slabs and spirals, in 1981 the Project contracted with the engineering firm Koogler and Pouls to produce terrestrial photogrammetric measurements of the site as an archive and as data for a computer graphics model. The exactness of some of the slab positions and shapes required to create the light patterns demanded fine precision in the construction of an archival computer model. For example, the Project estimated that a 1 cm movement of the eastern slab on an approximate north-south axis could create a 1 cm displacement of the lunar light patterns on the large spiral; a 1–2 cm movement of the top surface of the eastern slab on an approximate east-west axis could create a similar displacement (or blockage) of the summer solstice light dagger. Because the light dagger itself is only 2 cm wide, such a change would destroy the astronomical accuracy of the marking.

Disturbances of the Site

In 1981 the Solstice Project discovered, and then photographed, numerous disturbances and abuses to the Sun Dagger site: graffiti on the eastern slab, a beer can between the middle and eastern slabs, movement of several smaller rocks at the site, signs of removal of soil at the base of the middle slab, and loss of material along the edge of the eastern slab that cast the lunar markings (Sofaer 1982).⁵

In response to this documentation, the US Congress allocated \$100,000 to the National Park Service (NPS) for the development of a computer graphics model of the site. Congress proclaimed the Sun Dagger site a national treasure and recommended its thorough protection by the NPS (US Congress 1981). The NPS contracted with the consulting firm Ibarr, Inc., to develop a computer graphics model of the site. Ibarr contracted with two engineering firms—Aero-Metric and Dennett, Muessig, and Ryan—to produce a second set of terrestrial

photogrammetric measurements of the site in 1984, but it did not develop a model of the site from the resulting data.

In 1989 the Solstice Project discovered significant changes at the Sun Dagger site caused by natural erosion, greatly accelerated by tourist traffic and investigative activity. It appeared that the middle slab, critical to the shaping of all the solar light patterns, had pivoted about 2 to 5 cm from its documented position in 1978. Photo documenting of the effect of this disturbance by the Project and the NPS showed substantial changes: the slim, pointed summer solstice dagger of 1978 was now a wide band of light, the two winter solstice light daggers did not bracket the large spiral, and the small equinox light dagger did not pierce the smaller spiral (Palca 1989; Sofaer and Sinclair 1990).

The National Park Service's response was twofold: it limited visitation to the site more severely, and it brought in fill to replace the eroded sediments around the base of the slabs, constructing a coursed masonry wall east of the easternmost slab to prevent additional sediment loss downslope.

Computer Graphics Efforts

Throughout the 1980s and 1990s the Solstice Project pursued efforts to replicate the site, in consultation with experts in the burgeoning field of computer graphics. From 1979 to 1981 the Project turned to the Massachusetts Institute of Technology's Computer Graphics Department and from 1983 to 1987 to the Math Department at Rensselaer Polytechnic Institute (RPI). A graduate student at RPI, Eric Brechner, developed a prototype interactive model of the site on a Silicon Graphics computer (Bordner 1989; Sofaer, Sinclair, and Brechner 1989). In the early 1990s a graduate student at Ohio State University's Center for Mapping, Ken Edmundson, along with Phillip Tuwaletstiwa and Kurt Novak, developed a 3D model of a large portion of the site from the 1984 photogrammetric measurements. Novak combined Edmundson's digitized model with the interactive model from RPI to display on a Silicon Graphics computer a partial interactive model of the site (Novak, Edmundson, and Johnson 1992).

While these efforts paved the way, limitations in both the nature of the measurements to date and the available technology precluded the development of a fully and accurately functioning model of the Sun Dagger site. For example, the large photogrammetric cameras, which had to be stationary and at least 40 cm apart, could not adequately record within the crevice between the slabs and the spirals. This meant that Edmundson's model could replicate only the outer views of the rock slabs and not the spirals or the inner edges of the slabs, which cast half the shadow and light patterns that marked the solar cycle as well as the shadow patterns of the lunar cycle.

In 2001 Alan Price, of the University of Maryland, and the Solstice Project created an interactive model of the Sun Dagger site based on the Edmundson model. Now on display at the Adler Planetarium and Astronomy Museum in Chicago, Price's model allows viewers to move around the site and to view light patterns created on the spirals at different times of the day and year. Yet while educational and illustrative, the model is not an accurate or complete replication of the site. The Solstice Project's goal of developing such a model remained elusive.

DEVELOPING AND ORIENTING THE LASER-SCAN MODEL OF THE SUN DAGGER SITE _____

In 2003 Western Mapping Company's James Holmlund proposed that with new laser-scanning technology, his group could measure the inner edges of the slabs and the spirals, as well as the outer shapes of the slabs and the entire nearby cliff face and ground. Holmlund estimated that the results would be accurate within 1 cm, a level of precision at the low end of the range the Solstice Project had estimated would be required to authentically replicate the light markings.⁶

The assumption was that by now, all three slabs could have moved from their 1984 positions. The challenge concerned the plausibility of integrating two key sets of measurements: the accurate but limited and low sampling density of the 1984 photogrammetric data gathered before the site was disturbed, and the much more comprehensive and highly accurate laser-scanning measurements to come. The conclusion: the 1984 photogrammetric record had sufficient three-dimensional definition and accuracy—and, most critically, included enough tie-in with the cliff face—to allow a tight registration of the slabs of the proposed laser-scanned model with the slabs prior to their disturbance. Holmlund suggested that after acquiring three-dimensional laser-scan data for the current site configuration, the computer program could digitally separate the new slab models into their component parts and virtually reposition them to fit the configuration from the 1984 close-range terrestrial photogrammetric model.

With this assurance, the Solstice Project contracted the Western Mapping Company to conduct the laser scanning of the Sun Dagger site. Critical technical support came from the National Park Service, which wanted an archival record of the site in its current condition as a base for monitoring future changes. Following extensive logistical planning with NPS archaeologist Dabney Ford, the scanning effort proceeded with her generous assistance and that of professional climber Scott Sholes, several volunteers, and four members of the NPS ruins stabilization crew. A crew of thirteen hauled 670 pounds of equipment to the site, and two Western Mapping staff members, Joseph Nicoli and William Haas, conducted the laser scanning and surveying during the afternoon and night of May 11 and the morning of May 12, 2005.

Accompanying the group were William Stone of the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA), who would provide precise geodetic coordinates for the laser-scanned model, and Alan Price, who, with Stone and Haas, would conduct accurately timed photo documentation of the light patterns at the time of the laser scanning. Price, who would develop the final interactive computer model, would first use the photo documentation of May 11–12 to test the accuracy of the laser model with simulations of the light patterns on these dates.

Establishing Geodetic Orientation

On May 11 and 12, 2005, Stone positioned a permanent geodetic control point near the slabs. He established the geodetic position of the control point by collecting seventeen hours of static, dual-frequency GPS observations with survey-grade GPS equipment and procedures. The National Geodetic Survey's Online Positioning User Service (OPUS) utility processed the resulting data with respect to the nationwide network of permanent GPS Continuously Operating Reference Stations (CORS), which defines the nation's modern National Spatial Reference System. Peak-to-peak errors (that is, the approximate uncertainty of the results with respect to the CORS network) of about 1 cm horizontally and 2 cm vertically characterized the resulting geodetic position.

In addition, from May 11 to May 13, Stone collected GPS data on several vertical control points around Chaco Canyon to assess the accuracy and behavior of the GEOID03 model, which is used to convert between the ellipsoid height system (referenced to a mathematically defined surface, called the ellipsoid) used by GPS and the orthometric height system (referenced to a gravitationally defined surface, called the geoid) used on traditional maps to describe ground elevation. These additional observations indicated that GEOID03 works well in the Chaco area and that the resulting elevations derived from the combination of GPS measurements and the GEOID03 model are sufficiently accurate for this application.

Two sites provided azimuth control for the laser-scan work: a recently established permanent GPS installation on the mesa top north of Fajada Butte and a Public Land Survey System section corner positioned with GPS during the project. Both the GPS installation's monument and the section corner provide azimuth control for optical survey instrumentation (e.g., total station or theodolite) located at the Fajada Butte control point.

Verification of the May 11–12 results came with an independent survey by Stone of the Fajada Butte control point on December 16–17, 2005. The findings of a sixteen-hour GPS observation session, again processed through the OPUS utility, agreed with the earlier results within 0.5 cm in horizontal position and 1 cm in height.

Conducting the Laser Scanning

The Western Mapping staff carried out the laser scanning in two phases. In the first phase, the staff scanned the overall cliff face and most of the slab geometry with a Leica HDS 2500, which uses time-of-flight scanning. With this instrument, a laser scanner with a known relative orientation emits a laser pulse; the time the pulse takes to return to the scanner establishes a point at the measured distance and at the orientation of that pulse. The scanner runs through this process at a rate of a thousand times per second, creating a point cloud. The scanner is then moved to another position, where the process is repeated. Setting the instrument in various locations allowed the Western Mapping staff to capture complex shapes, with intricate relationships, in three dimensions. The cliff face was scanned at a density of points of 1 cm (that is, a point was collected every centimeter), and the slabs were scanned at a resolution of 5 mm. The scanner recorded a total of 7.2 million points from thirty-one different scanner setups.

In the second phase, the Western Mapping staff conducted small-scale triangulation scanning of the two spiral petroglyphs and most of the shadow-casting edges of the slabs. The triangulation scanner consists of a camera and a line laser. The laser passes over the area at a known rate, while the camera captures 3D coordinates, triangulating among the camera, the laser, and the rock surfaces. Western Mapping staff conducted seventy-one triangulation scans of the scene, all with an estimated accuracy of better than 1 mm. (Because the pixel count of the camera determines the resolution of the final image, resolution cannot be precisely quantified.)

Registration of the Laser Scans

The Western Mapping staff completed the registration in three phases. In the first phase, the time-of-flight point clouds were registered locally to each other. Targets placed in the scanned scene act as 3D reference points to which overlapping clouds can be registered. In addition to the targets, a process called cloud-to-cloud registration uses similar geometry in overlapping scans to align two scans to each other. The computer operator tags two point clouds that roughly identify areas of overlapping geometry. Software algorithms then create a best-fit alignment of the two clouds. Repeated multiple times between various clouds, this process creates an overall best-fit alignment. Incorporating the targets and the cloud-to-cloud alignments, the final local registration is frozen.

In the second phase of registration of the laser scans, the Western Mapping staff put the locally registered scans into a geodetic coordinate system so the scan information could be modeled later with respect to astronomic relationships. Using the geodetic positions established by William Stone for the new

NGS monument (station FAJADA) on Fajada Butte, the staff computed a geodetic azimuth and a Universal Transverse Mercator (UTM) azimuth between FAJADA and the CORS station previously established at Chaco Canyon. (The UTM is a universally used x-y planar mapping coordinate system, which is rigorously related to the geodetic latitude-longitude system.) The staff checked these orientations against the position of another GPS-positioned section corner monument more than 1.5 km from the site. Using a certified geodetic-quality total station, the staff mapped the positions of reflective targets in the scan scenes and established world (UTM) coordinates for each target. These coordinates were then adjusted (see the section “Positioning and Orienting the Laser-Scanned Model”) and incorporated into the cloud registration, moving the local registration into UTM-based coordinates.

In the third phase, the Western Mapping staff used a different software program to group the small-scale scans into five areas and register them to each other using the cloud-to-cloud method just described. The world coordinate registered group was then imported into the new software, where the overall cloud-to-cloud registration was further refined. Again using the cloud-to-cloud method, the small-scale scan groups were then registered to the world coordinate group.

Modeling the 2005 Laser-Scanned Site

To model the laser-scanned site, the Western Mapping staff moved both groups of scanned data—the time-of-flight and small-scale scans—into a different software program. With the time-of-flight point data reduced in resolution to eliminate overlapping data points, a Triangular Irregular Network (TIN) was created at approximately 6 mm resolution. Each of five additional small-scale scanner models was decimated to 0.8 mm resolution and meshed independently. The resulting high-resolution models were pasted into the overall model. These high-resolution portions simply replaced less resolved sections (at 6 mm resolution) modeled from the time-of-flight data. The models were cleaned of spurious data and resampled using curvature-based algorithms.

Positioning and Orienting the Laser-Scanned Model

Because the survey was adjusted to the UTM coordinate system, an additional rotation was necessary to establish the geodetic orientation to match the input required for Alan Price’s astronomical modeling program. The Western Mapping staff used the convergence angle between the UTM coordinates and geodetic positions computed from the reduction of the GPS data at station FAJADA to rotate the orientation of the model to geodetic north. Since the coordinates were originally

UTM grid coordinates, they used the computed ground-scale factor for FAJADA to scale the coordinates to enable accurate (local) model measurements. At this juncture, the coordinates of this adjusted (Sun Dagger site) system were no longer UTM coordinates but instead a local coordinate system.

Testing the Accuracy of the Laser-Scanned Model

To test the new model, Price used the accurately timed digital photographs and slides of the light and shadow formations on the spirals and the surrounding cliff face taken during the two days of laser scanning—two sequences of images made during midday on May 11 and 12 and a third of sunrise on May 12. Independent of the fact that the light patterns have changed since the site's initial documentation in 1978, it was critical that simulations of light and shadow casting on the new digital model exactly match the site in its May 11–12, 2005, state.

To facilitate testing of the model before developing the interactive application, Price selected Alias Maya software because of its suitability for handling the high-resolution model, for ray trace rendering, and for the custom scripting ability of Maya Embedded Language (MEL). In Maya, a directional light model was used to project orthogonal (parallel) light to ray trace shadow patterns from the slabs to the cliff face based on ephemeris calculations of the sun and moon positions. (An ephemeris is a table of the positions of a celestial body at regular intervals.)

To calculate the ephemeris, a series of MEL scripts was created that interfaced with an external application for the calculations. Code was compiled from Steve Moshier's AA code (www.moshier.net) for computing ephemerides of the sun and moon using rigorous reduction methods from the *Astronomical Almanac* and related sources and a long-term extension of modern lunar theory for the moon's position. The results of the calculations were compared with the US Naval Observatory's ephemeris calculations and with a number of commercial planetarium software programs, including Starry Night Pro, Software Bisque's The Sky, and Sky Map Pro. The UTM coordinates and elevation obtained during the process of scanning the site were used as input parameters for the ephemeris calculations. A series of renderings was created with the digital model to correspond with the timing of images taken May 11–12, 2005.

The first results proved a highly accurate match of light patterns between the simulation and the photographic documentation, indicating that the processes of scanning, gathering positional and orientation data by the Western Mapping Company and William Stone of NGS, and Western Mapping's conversion process of the digital model had created an accurate digital reproduction of the site as it existed on May 11–12, 2005.

In the spring of 2006, Aero-Metric, under the direction of Andrew Piscitello, conducted further readings of the 1984 photogrammetry, which consisted of eleven stereo pairs of glass plates recorded by Dennett, Muessig, and Ryan. A special effort was made to include as many data points as possible in this reading that would accurately relate the slabs to the cliff face, on the assumption that all three slabs might have moved by the time of Western Mapping's 2005 laser-scanning project. The cliff provided the only stable feature of the site for both the 1984 and 2005 models of the slabs.

Background: 1984 Photogrammetric Activity

In 1984 Dennett, Muessig, and Ryan had acquired eleven stereo pairs of photography of the Sun Dagger site on glass plates using a WILD 40 dual camera system. This system is composed of two calibrated metric cameras mounted on a fixed base bar to ensure that their optical axes are parallel. Positioned a proper distance from an object, the system records overlapping images suitable for stereoscopic viewing. With a stereoscopic restitution instrument to record x, y, and z positions of any point imaged in the object space, precise measurement is then possible from the stereoscopic images.

Dennett, Muessig, and Ryan had also conducted a field survey to determine the x, y, and z positions of control targets—small concentric rings (a bull's-eye) affixed to the surface area of interest—which would reestablish the position of the cameras during the photogrammetric restitution process. The object of the surveys, completed in a local coordinate system with Polaris observation (to determine true north), was to tie the observations to previous surveys by Koogle and Pouls that had located the site in geodetic position. The surveyors used a WILD T2 theodolite to attain their readings. The field surveys were designed to produce accuracies in the range of 2 mm.

Dennett, Muessig, and Ryan contracted Aero-Metric to reduce the fieldwork surveys and complete the photogrammetric restitution. Aero-Metric reduced the survey work in the local coordinate system with orientation to true north but did not transform the results to the actual geodetic location because the necessary data were not available. In 1984 Aero-Metric completed an analytic triangulation of all the photographs and produced a simultaneous adjustment of all the photo positions to verify the control points. The photogrammetric restitution of each of the eleven stereo models was then completed on a WILD BC1 analytical stereo plotter, and several thousand points on the surface of the Sun Dagger slabs and on the large and small spiral petroglyphs were recorded. The photogrammetric

accuracies varied from a couple of millimeters to approximately 10 or 12 mm, according to the variation in the distance of the cameras from the image points. This effort did not produce a complete computer model of the Sun Dagger site because the dataset was not sufficiently dense and the system was unable to measure points within the narrow openings between and behind the slabs.

2006 Photogrammetric Reading

In the spring of 2006, at the request of the Solstice Project, Aero-Metric used the 1984 photogrammetry survey to add points on the cliff wall, against which the slabs were positioned, to its original readings of this dataset. The stable cliff wall and its features were accurately shown in the LiDAR dataset. In particular, Aero-Metric added readings from the 1984 dataset of micro-topographic features of the cliff wall so the photogrammetric model could be accurately transformed to the 2005 laser-scanned model.

For this new work, the individual stereo models were reset on a Zeiss P1 analytical stereo plotter. Once the existing dataset was verified, Aero-Metric added new recordings of x, y, and z coordinates of the significant features on the cliff wall the Western Mapping Company had identified, based on the laser-scanned data, as critical areas for registering the two models. These features could be readily identified in the LiDAR dataset. The resulting new, more comprehensive (1984) photogrammetric model was transferred to the Western Mapping Company in Tucson.

REGISTERING THE 1984 PHOTOGRAMMETRIC MODEL WITH THE 2005 LASER-SCAN MODEL _____

Western Mapping Company staff digitally removed the disturbed slabs in the 2005 laser-scanned model, maintaining only the laser-scanned cliff face. They then registered the slabs and the cliff face of the new 1984 photogrammetry model to the laser-scanned cliff face. Using cloud-to-cloud registration, they then registered each of the laser-scanned slab models that had been digitally removed to its corresponding, pre-movement version in the new model. The resulting registration was frozen as the 1984 model.

Beyond an attempt to digitally restore the slabs to their 1984 positions, this registered model contained remarkable detail of the site, with more than 30 million points compared to the 9,000 points of the 1984 photogrammetry. (The significantly smaller number of points in the 1984 model did not detract from its high accuracy in modeling the slabs and their relationship to the cliff face because the points were collected in smaller critical areas of the slabs and bedrock identified in

the laser model.) The laser-scanned model covered far more of the site than did the 1984 photogrammetry, encompassing the surrounding cliff and ground areas up to 5 m above the slabs, 3 m to the east, and 3 m to the west. For example, it recorded a critical shadow-casting edge located approximately 4.7 m above the slabs, in an area suspected and later specifically identified as defining the upper edges of the light daggers in the summer season.

In addition, the new model made possible an accurate geodetic orientation, which the 1984 photogrammetric survey had not obtained, derived from the 2005 geodetic positioning of the FAJADA monument at the site by NGS.

TESTING THE ACCURACY OF THE REGISTERED MODEL _____

To test the accuracy of the registered model from Western Mapping, in the spring of 2006 Alan Price applied the astronomical program he had used in his test of the 2005 laser model. As an integration of the detailed 2005 laser-scanned model into the 1984 photogrammetric model, the registered model should have restored the slabs to their positions prior to their disturbance and thereby simulated images of the light patterns, replicating the early photo documentation of the site.

Price's test results showed that the solar and lunar images simulated by the registered model match the Solstice Project's accurately timed photo documentation of solar and lunar events at the site in the years 1978–1987.⁷ (In addition to the set of sequential photographs taken by Karl Kernberger, numerous other timed photographs had been taken of lunar and solar events at the site.) The paired images in figures 3.2 and 3.3 show light and shadow markings photographed between 1978 and 1983 at the key times of the solar and lunar cycles compared with those simulated by the registered model at these times.

The Solstice Project's first goal was now a reality: an archival digital replication of the Sun Dagger and its astronomical functioning.

ASSESSING THE SITE'S DISTURBANCE _____

Using the two models—the 2005 laser-scanned model and the 1984 photogrammetric model—Price and Western Mapping explored the extent of disturbance to the slabs. Figure 3.4 illustrates Price's comparison of the simulated slabs restored to their 1984 positions, shown in solid form, and the 2005 disturbed slabs, shown in black outline. The middle slab had moved the most of the three—15 cm on one axis. The other two slabs had also moved: the eastern slab 5.4 cm on a similar axis and the western slab the least, 0.8 cm.

EXPERIMENTS WITH THE GEOLOGICAL HISTORY OF THE SUN DAGGER SITE _____

Preliminary experiments with the 2005 registered model have placed the slabs in the positions where, according to geological reports (Newman, Mark, and Vivian 1982; Sofaer, Zinser, and Sinclair 1979), they were originally attached to the nearby cliff along an approximate horizontal plane. Plans call for more detailed efforts to match the geometry of the cliff face with the inner surfaces of the slabs to verify or refute these earlier reports and possibly to further pinpoint the slabs' place of origin. With the slabs attached to the cliff in the computer model, planned kinetic experiments should show possible positions to which they could have fallen and been found by the Chacoans.⁸

CREATING AN INTERACTIVE RESEARCH MODEL _____

In 2006 Alan Price created an interactive application for research and analysis of the site. The application combines functionality similar to the tools created with MEL scripting with new navigation and manipulation tools so researchers can explore the model in a standalone application.

The interactive application allows one to navigate around the 3D model, observing it from any angle. One can set the calendar date and the time of day for positioning the sun and moon, projecting the shadows of the stone slabs onto the cliff and spiral patterns in real time. Translation and rotation tools allow one to experiment with manipulation of the slabs and the cliff face in the region of the spirals, as well as to alter the latitude, longitude, and orientation of the entire site. One can set markers at any position on the surface of the slabs or cliff face to measure distances between points and to determine shadow-casting edges. A surface modeling tool allows one to alter the shape of the slabs, much as one might use a small tool to work the shadow-casting edges. One can alter the orientation and size of the spiral patterns or "draw" an entirely new spiral. These tools allow a user to deconstruct the site, experimenting with variations to gain a better understanding of the complexity and precision with which it operates.

CONCLUSION _____

Through the extraordinarily generous and dedicated efforts of many individuals who have brought rich interdisciplinary experience to the project, the Chacoan Sun Dagger is digitally restored. It is also accessible for challenging research explorations and, it is hoped, will serve as a stimulating educational resource.

Centuries ago, the Sun Dagger site engaged skilled and trained astronomers to achieve its complex astronomical expressions. It is of interest that its restoration

required several of today's most advanced technologies, employed by scientists with modern math and engineering backgrounds.

Several mapping specialists from Western Mapping Company and a geodesist ensured remarkable precision and scope in the laser model's replication of the site and its orientation. Photogrammetrists provided high-quality stereo glass plates of the site before its disturbance. They also provided thorough readings of these plates for the intricate detail essential for the registration of the recent laser model to the model of the site prior to its disturbance. Recently developed computer software allowed the registration of the two models. Finally, a computer modeler, using the latest programs of astronomical data and sophisticated interactive computer applications, could test the model of the restored slabs against the 1978 accurately timed photo documentation of the astronomical markings of the site. The success of the digitally restored model is evident in its exact replication of this early record, with no manipulation of any element in the model.

In contrast, about a thousand years ago the Chacoans developed the site by applying their knowledge of the solar and lunar cycles and their astute observations of shadow and light patterns to three sandstone slabs located near a south-east-facing cliff face. As in the alignments of their buildings, in the light markings of the Sun Dagger site the Chacoans developed an integrated expression of the sun and moon. This site and the Chacoans' other elaborate astronomical works are physical realizations of cosmological concepts.

The detail and precision of the research model, with its numerous interactive tools, offer opportunities to analyze the Chacoans' process. Experimentation with the model should bring insights about the knowledge, planning, and experimentation the Chacoans employed to achieve the interlocking markings of the sun and moon. It has already revealed to one researcher elements of the site that were readily available and suggestive to Chacoan astronomers (Luce and Sofaer 2009).⁹ Further exploration may reveal the Chacoans' process of refining their light markings by shaping, moving, or adjusting elements of the site.

Perhaps, paradoxically, only an interactive research model achieved with the latest technologies will allow modern researchers and students to appreciate the Chacoans' capacity to conceptualize and work—without such technology—with the four dimensions of time and space as they created the Sun Dagger site.

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Survey of NOAA again assured us the assistance of William Stone in producing a superbly precise geodetic survey of the site. We thank Phillip Tuwaletstiwa for his early and continuing interest in the Sun Dagger modeling effort and Kenneth Edmundson for his dedicated work to create the early photogrammetric model of the site. In 1984 Dennett, Muessig, and Ryan recorded the precise photogrammetric stereo pairs used in the final modeling. The Center for Mapping at Ohio State University, the Imaging Research Center at the University of Maryland, ACCAD at Ohio State University, Aero-Metric, Inc., and Cooper Aerial, Inc., provided critical technical assistance to our modeling efforts. We thank NPS archaeologist Roger Moore and volunteers Scott Sholes (Durango, Colorado), Susan Yewell (Solstice Project), Craig Johnson (Santa Fe, New Mexico), Armando Espinosa Prieto (Santa Fe, New Mexico), and Richard Friedman (Farmington, New Mexico) for their generous logistical and safety support of our laser scanning of the Sun Dagger site in May 2005. Lindsay Kraybill (Western Mapping Company) provided critical data analysis in developing the 2005 laser model and the registered model.

NOTES

1. The Solstice Project (www.solsticeproject.org) is a nonprofit organization dedicated to the study of ancient cultures of the American Southwest. The organization was founded in 1978 by Anna Sofaer to study, document, and preserve the Sun Dagger and other astronomical expressions of these cultures.

2. These references discuss possible cultural affiliations of the Sun Dagger site and contain estimates of the time of its development between AD 900 and 1300, as well as describe certain parallels between the Chacoan astronomical expressions and the traditions of historic Pueblo cultures.

3. It is difficult to strictly define at what point the shadow and light formations of the rising major and minor standstill moon and the equinox sun can be considered “markings.” These formations appear to be distinctive patterns (i.e., close to the edges and the center of the large spiral), however, when they are cast by the sun or moon rising within 0.5 to 1.5 degrees of the values given here of azimuths 54.3, 67.1, and 90 degrees (see Sinclair and Sofaer 1993 for a discussion of how these values were established). In our documentation, we define “rising” as when the sun or moon is 0.5 to 1.5 degrees above the 0.3-degree altitude of the eastern-northeastern horizon. See annotations to figures 3.2 and 3.3 for the specific azimuths of the solstice, equinox, and lunar standstill light and shadow markings illustrated in this chapter.

4. The right and left edges of the large spiral are marked multiply: at the winter solstice with two light daggers on these edges, at the equinox by the rising sun’s shadow on the right edge, and at the major lunar standstill by the rising moon’s shadow on the left edge. In addition, both the minor standstill moon’s shadow and the summer solstice sun’s light dagger mark the center of the spiral. Finally, the summer solstice dagger also marks the top turn of the spiral: for the four to five days before and after the summer solstice only, the light form first appears as a spot of light in the top turn. (A week after summer solstice,

a streak of light appears above the spiral and expands through the seasons.) In sum, these numerous interlocked markings appear to define the shape and size of the large spiral. (For a fuller discussion of this apparently intricate coordination of the markings at the site, see Sofaer and Sinclair 1987.)

5. NPS records showed that more than a thousand registered visitors had been to the site between 1977 and 1982. Many others, it is assumed, visited the site without registering with park staff (Trott et al. 1989). See figures 3.3b(1) and (2). The loss of material along the shadow-casting edge of the eastern slab caused the difference evident between the image of the 1980 photograph 3b(1), taken before the loss of this material, and the simulated image of the same, derived from the laser scan that registered the change, 3b(2). See in particular the difference in the shadow line below the spiral center.

6. As it turned out, the laser model has only about half the inaccuracy Holmlund had estimated.

7. Experiments conducted with the model since 2008 uncovered an earlier timing in the first appearance of the light dagger at summer solstice when compared with the 1978 photographic record. Calculations by Alan Price and Ben Luce, who studied this phenomenon on the model, and consultations with James Holmlund suggest that the rock face immediately above the large spiral is within a configuration of the slabs and the cliff face that is too narrow to have allowed accurate laser scanning. This rock surface casts the shadow that forms the top edge of the light dagger when it first appears on the large spiral. It is hoped that with new laser-scanning equipment available and with the assistance of the National Park Service, the Project will have the opportunity to scan this surface successfully in the near future. At that time the early occurrence of the light dagger can be studied and assessed, including the possibility that a small settling of the slabs between 1978 and 1984 widened the opening between the eastern and middle slabs and thus caused this earlier occurrence of the light form.

8. In 1982 three authors reported their geological and archaeological assessment that the slabs could have fallen into their 1978 recorded positions (Newman, Mark, and Vivian 1982), refuting an earlier report by the Solstice Project (Sofaer, Zinser, and Sinclair 1979). This report strongly implied, by its title and concluding statements, that there had been no movement of the slabs by the Chacoans, although it provided no data to exclude this possibility. Following this proposal, Newman and Mark were reported to have stated that the slabs could have been adjusted and shaped to achieve the markings (Simon 1982). See Sofaer and Sinclair 1987 for discussion of the likelihood that the Chacoans achieved the complexity of the solar and lunar markings at the site without some adjustment to the slabs.

9. Ben Luce, a theoretical physicist, recently initiated a study of the Sun Dagger site's functioning, using the interactive tools of the computer graphics model and other theoretical models based on the interactive model, to explore the mechanisms involved and possible constructive aspects. He reports that preliminary research "reveals a fully but not overly determined system in the way the site controls a complex set of astronomical and geological variables to achieve its markings" (private communication 2009; Luca, in press).

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