

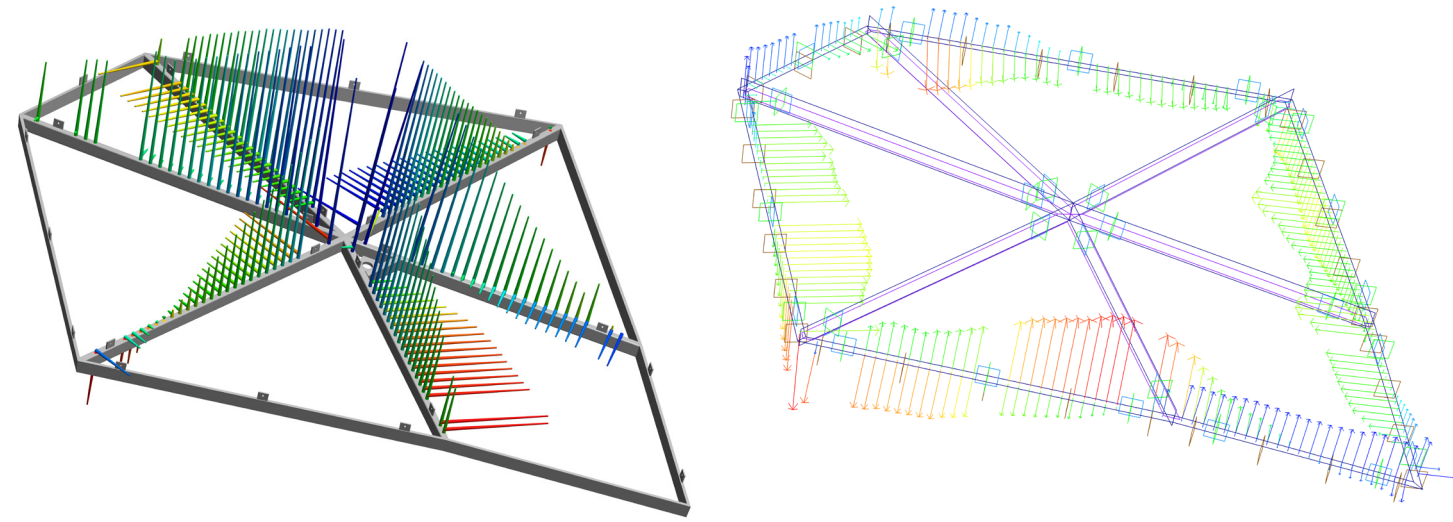


## NOVEL USES OF METROLOGY ON GEOMETRICALLY COMPLEX FACADES

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As software and technology advances in the building sector, the ability and willingness to design more complex and intricate structures grows. Constructing these buildings needs the same level of technological advantage as the design took. One means of supporting complex projects is the use of laser tracking metrology to precisely measure and guide work. This can be done during fabrication or afterwards to verify accuracy. An example of this process was implemented and utilized throughout the construction of a complex glass dome project. Laser tracking metrology was implemented during fabrication and at quality control checkpoints throughout project schedule. The use of parametric software during the design phase of the project complimented the laser tracking methodology through automated digital model formation. 3D printed components were used to augment the accuracy of existing laser tracking tools and to guide laser-assisted fabrication efforts.

Laser tracking technology consists of a low-powered laser mounted on a tripod with an unobstructed view of the object to be measured (Fig. 1). The mounted laser can move about two axes – azimuth and altitude via a rotating head. A spherically mounted retroreflector (SMR) acts as the target for the laser tracker, while an absolute distance meter (ADM) measures the distance from the laser tracker to the target and back. This spatial information (azimuth, altitude, and distance) produces a coordinate location relative to the tracker's position. The accuracy of the laser tracker is extremely precise, measuring down to 0.005" over a distance of 80 yards. Coordinates can be recorded in several ways – distance-based intervals, skip-stop time intervals, or full stops. A measurement could be taken every one inch the SMR travels along the surface of an object, every time the SMR is held in a stable position for at least one second, or just one measurement at a stable position. The coordinate information is transferred back to a computer interface which displays the coordinates and populates 3D model space in real time.



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 FIGURE 1  
 Omnictrac2 laser tracker with the SMR  
 at home position.

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 FIGURE 2  
 Various visualizations of scanned data  
 over 3D modeled components.

The coordinate data shows points in space relative to the location of the laser tracker. After the points are gathered, relationships between the groups of points measured on a physical component and a predefined 3D modeled component are generated. These relationships allow the spatial analysis software to re-map the location of the gathered dataset (coordinates in relation to the tracker's location) to align with surfaces on the 3D modeled piece. Once the measured dataset is aligned, the relative differences between it and modeled components can be studied. Magnitudes of differences can be measured and visually displayed or tabulated for export (Fig. 2). Variations of colors and transparency options help to visualize where and by how much things are not matching up. Another benefit of the model being aligned is that as future coordinates are measured they appear neatly aligned already and readily producing information. This can be used to

back-check and verify a quick spot check of an already measured component or help guide the placement of pieces in the field with extreme precision.

This type of laser tracking metrology had been introduced on a large-scale complex facade project in New York City. It was brought in to measure and correct issues with several layers of a intricate metal panel unit during shop fabrication (Fig. 3). Originally brought on to study the issues from the structural steel sublayer, the value brought by the laser tracker became apparent in all aspects of the panel unit fabrication. By the end of fabrication the units were down to a finished tolerance of  $\pm 1/32"$ , an incredibly tight assembly. The decision to implement the tracking metrology on this new complex glass dome project was based on the success and extreme value it had brought to the New York project.



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FIGURE 3  
NYC project panel assembly guided by laser tracking metrology.

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FIGURE 4  
Steel shell and glass units installed, taking the form of conjoined domes.

The main implementation of the laser tracking was a complex glass dome project consisting of three spheres of varying radii (42.5 to 65 feet), joined together and subdivided with a repeating pentagonal pattern. 29 types of pattern cut pieces of glass make up the pentagonal subdivision that is repeated across all three spheres (Fig. 4). To support the various shapes and sizes of captured glass cassettes, steel tabs are located below the glass system carried by a steel tube and bar secondary support system. The secondary and primary steel support systems are derived from the glass pattern above. Six secondary steel frames are bolted together to form a “super pentagon” that is anchored to the primary steel beneath it. The secondary steel system forms a continuous shell structure to the support the glass. Over 9,000 steel tabs, bolts, and unique steel elements dot the secondary steel structure across the spheres.

Between the sheer number of components and the tight tolerance across the enclosure system it became apparent that a specialized approach to fabrication and quality control would be required.

A preliminary laser scanning was conducted on the performance mock-up portion of the project. A plan was devised on how to tackle the scanning and coordination for each frame and componentry. Each frame would be scanned, covering each outer bar, inner tube members, anchor locations, steel tabs, bolt hole locations, and any miscellaneous steel plates. Each scan of the steel members would be used to link up to the digital model for comparison; the highest coordination priority would be the location and orientation of each of the steel tabs - the tabs had the tightest design tolerance and were the link between the glass and the steel systems.

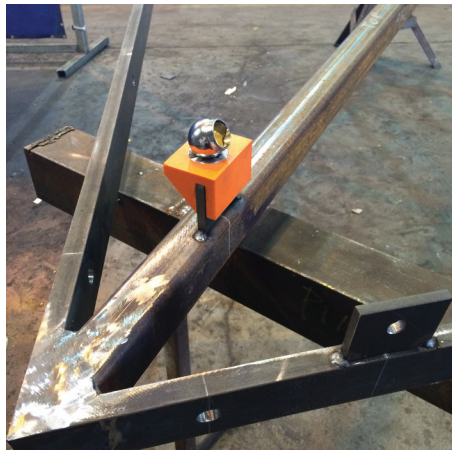
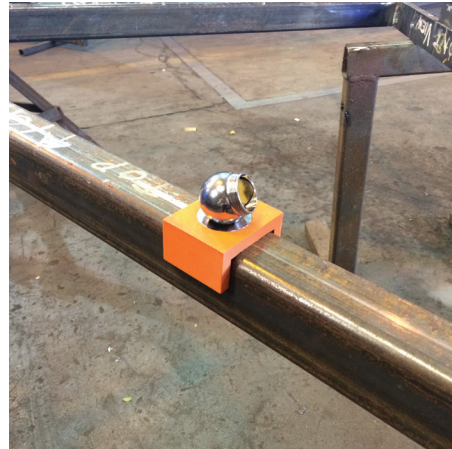
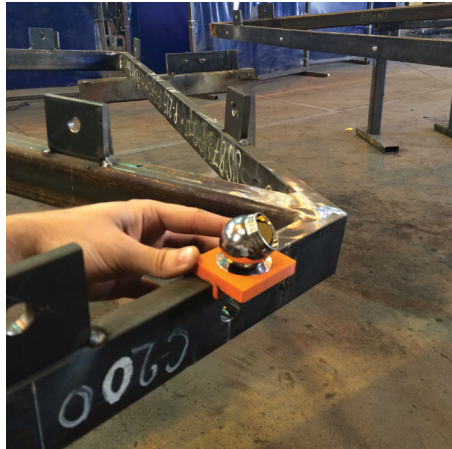


FIGURE 5  
Exterior steel bar measuring adapter.

FIGURE 6  
Interior tube steel measuring element.

FIGURE 7  
Shaped steel tab measuring component.

FIGURE 8  
Slotted bolt hole measuring piece.

FIGURE 9  
Anchor location measuring part.

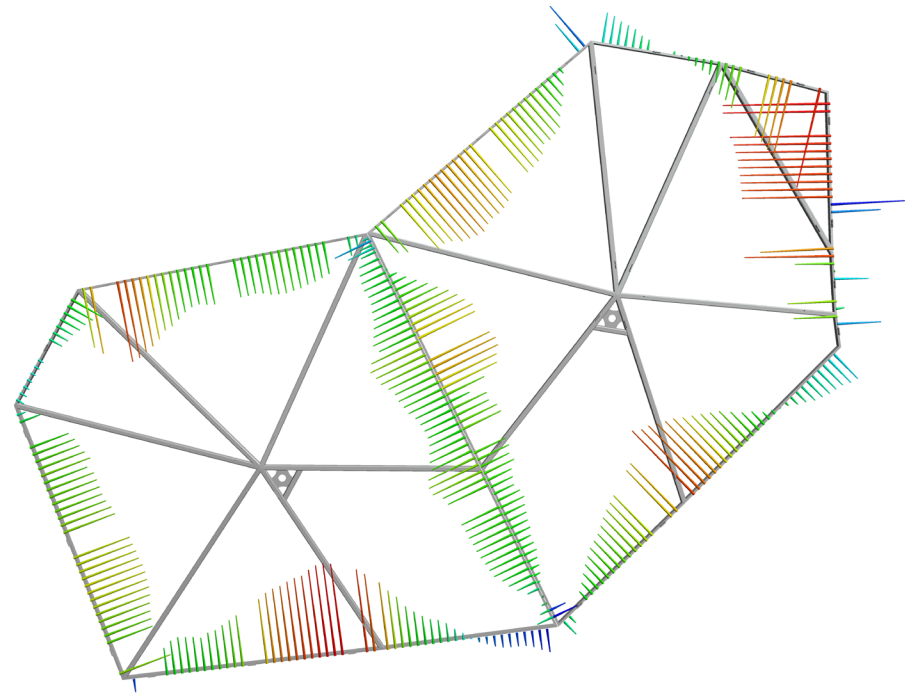
FIGURE 10  
Collection of 3D printed components used to augment the laser tracker's SMR.

The default toolkit for the laser tracker was a set of stainless steel adapters with a magnet that the SMR sits in and could fit in holes or glide along edges. However, to properly capture the steel frames unique geometries and smaller components, a more customized set of adapters for the SMR would need to be created. Using 3D printed prototypes, iterations of plastic components were modeled and printed that would augment the default tracker adapters to fit perfectly on the steel tabs, tubes, or shaped anchor locations. Five 3D printed components were developed and produced:

1. A deeper edge adapter to capture and measure the exterior steel bars (Fig. 5).
2. A hanging element to glide along and measure the top centerline of the steel tubes (Fig. 6).

3. A triangular block component to measure the center and orientation of the steel tabs (Fig. 7).
4. An elongated circular piece that plugs into the slotted bolt holes (Fig. 8).
5. A cross-shaped part which sat in the anchor hole center and measured its location (Fig. 9).

As each piece was used, running over the steel repeatedly, they would wear down over time and needed to be replaced to maintain proper levels of accuracy. These replacement pieces were opportunities to be improved on, and over the course of fabrication schedule evolved into better and more efficient measuring tools. Different colors represent different batches of components, with some new pieces acting as adapters to the adapter piece itself (Fig. 10).



Prior to scanning each steel frame, a digital model of that same frame needed to be created to match the physical and scanned representations together. Fortunately, since the beginning of the design phase of the project, parametric models in the form of Grasshopper and Rhino files were being developed. These parametric models held embedded data in simple line and point models that could be adapted into the specific surface based models to conduct the spatial analysis comparisons. A workflow was created to convert every “super pentagon” frame model into a series of planes and points that would represent the physical steel frame. Hundreds of models were efficiently converted this way and prepared for the laser tracking coordinate overlay.

Once each frame was scanned and mapped together with the digital models, the relative

differences could be studied. Besides spotting steel that was out of plane or elements misplaced – the scans could even be stitched together to confirm frame to frame bolting connections were coordinated (Fig. 11). Magnitudes of difference greater than the project tolerance of 1/4” were flagged and highlighted on the shop drawings to identify which areas of the frames needed corrections (Fig. 12). The process of identifying areas of remediation and recording everything in a spreadsheet was used to convey information back to the steel fabrication. If excessive errors were discovered on a frame, a second scanning pass would be done after the intended fixes were completed to verify all issues were corrected. Over time the spreadsheet was used to track progress on the corrective measures completed by the steel fabricator and to assess future time commitments for the laser scanning (Fig. 13).

The more traditional role of laser tracking as a means of quality control worked well for the majority of frames, identifying small problems such as missing elements, pieces to be adjusted, or parts to be replaced, but some frames came up with extreme issues that required entire frames to be rebuilt. In those instances it became apparent that it would be easier if the placement of elements were actually guided by the laser tracker, rather than checked afterwards. One example was the steel tabs. They were guided into position using the laser tracker and spatial analytics software which displayed the proximity to the exact location in real time. Once in place, a chalk outline was scribed on the base steel around the tab and it was tack welded in place where it was re-measured and its location confirmed to be exact.

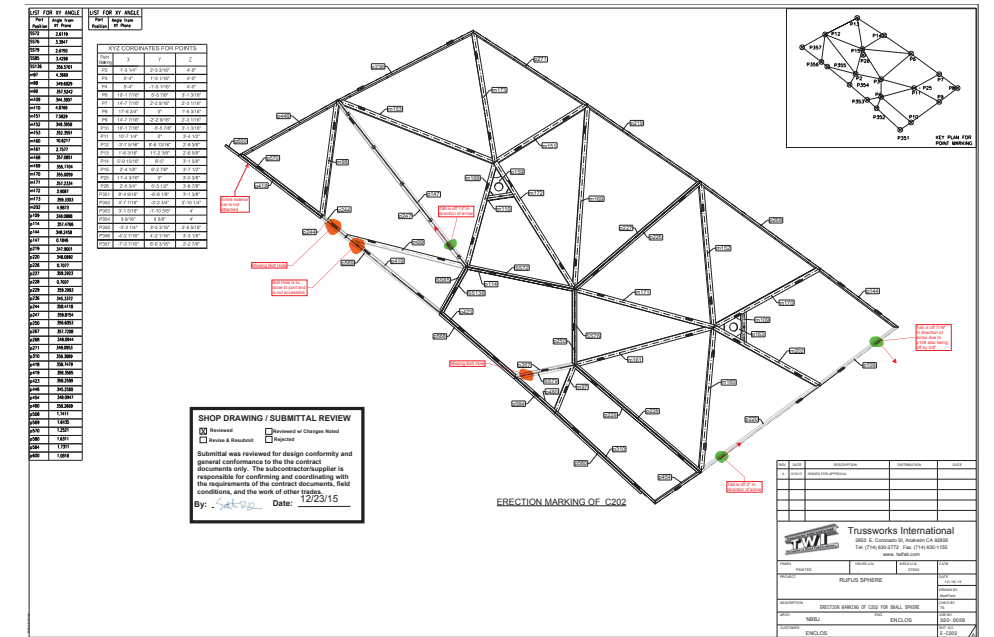
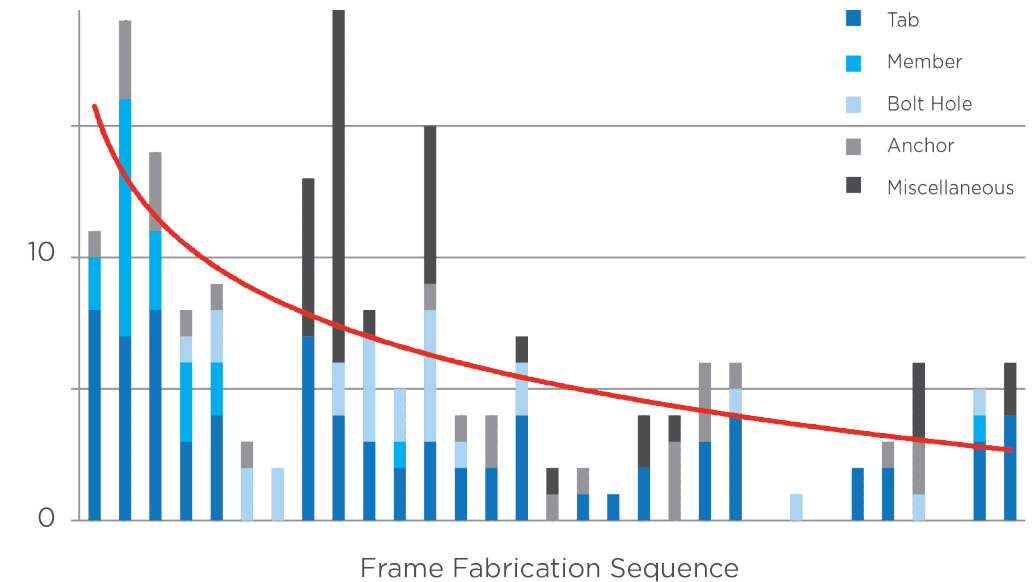


FIGURE 11  
Two models stitched together, verifying their edge steel bars mate correctly.

FIGURE 12  
A shop drawing marked up with areas out of tolerance to be corrected.

FIGURE 13  
Types and quantity of errors found through the laser tracking process on the first 25 frames, showing improvement as time progressed.





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FIGURE 14  
Verifying the steel tab is in the correct location after being welded in place.



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FIGURE 15  
Locating and marking the steel tab with the laser tracker.

When a new type of frame was added to the scope of the project, it was determined that it would be exclusively fabricated with laser tracker guidance. New 3D models and custom prototyped tools were created to fit the demands of the new steel frames, some over 40 feet long and 15 feet tall. In addition to the difficulty of working with double-curved steel members, the frames were delivered with serious issues from the steel rolling fabricator and could not be fixed in time to meet the schedule. The original plan was to scan and locate similar steel tabs to the previous frames; however since the base steel tubes were inaccurate, the tabs would also need to be cut to length in addition to being placed. Hundreds of steel tabs were guided into place, marked, cut to size, and installed (sometimes 15 feet high and upside down), all falling within the 1/4" project tolerance (Fig. 14-15).

Over 500 frames were scanned and released for installation over a period of one year. Six miles of steel and approximately 9,000 steel tabs, bolt holes, and miscellaneous steel elements were graced by the 3D printed components and measured into digital space. Every frame that was scanned and approved by the laser tracking metrology was installed on the project with no issues on site. The laser tracker performed well across a broad range of issues, its capabilities extended with the novel introduction of 3D printed components. The combination of powerful parametric modeling, laser tracking, and rapid prototyped tools provide a successful example of how new technologies and software can bring value to complex construction projects.