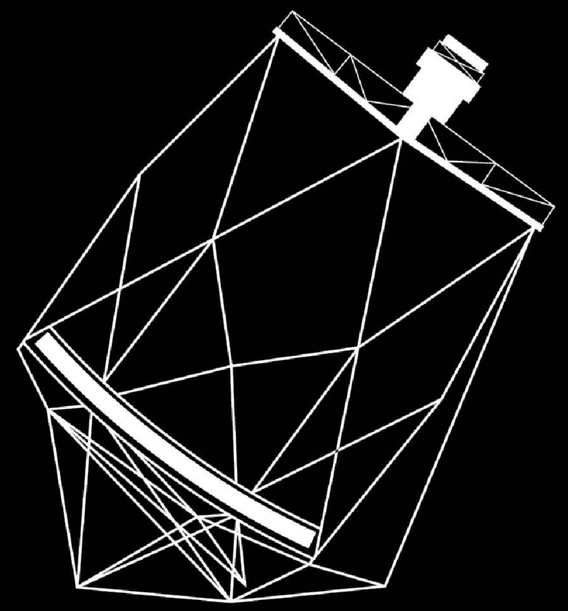
2023

JACOB LEAVENGOOD

S.T.R.A.T.A.



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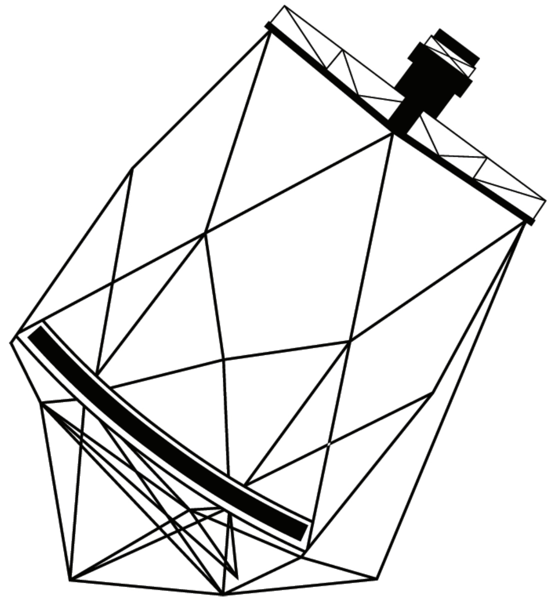

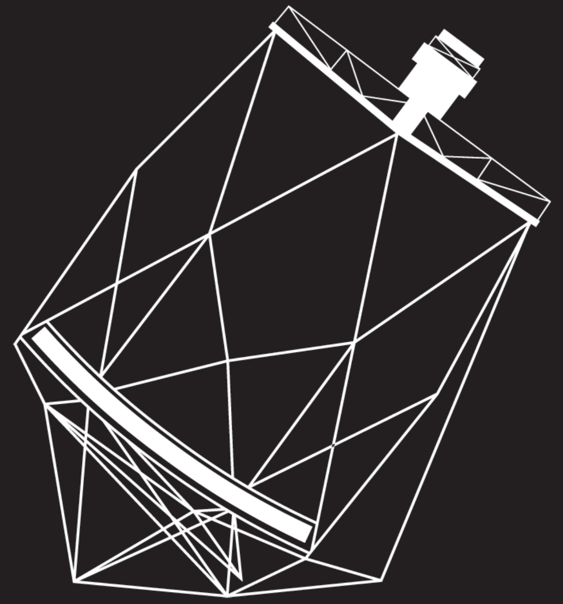

S.T.R.A.T.A.

Layer by Layer

Jacob Leavengood

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Laters of the Earths Atmosphere *Figure 1*

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Milky Way Over Palo Duro Canyon *Figure 2*

Introduction

As long as I can remember I have always had an interest in the stars and observing the night sky. I fondly remember times in my childhood where I would wake from bed late at night, shaking off the grogginess, and making my way outside to see a lunar eclipse, a blood moon, or a meteor shower. Whether it was staring through my childhood telescope, taking trips to the local planetarium, road trips into the dark night sky, watching science documentaries, or simply reading science-fiction, I have pursued my upward gaze my whole life.

As I progressed my professional education, I found myself studying how observatories operate, how astronomers watch the night sky, and how colonists of the future might someday live on other planets. The ideas felt far off and distant, both in time and space, but emerging construction methods are making these science fiction ideas more possible. Three-dimensional printing (3D printing) construction is at the forefront of this trend. The robotics added assembly, and the seemingly endless combination of printing mixtures create ideas of other-worldly buildings constructed -in and -of the alien landscape in which humans observe and might one day inhabit.

At the same time, 3D printing is a ‘down-to-Earth’ construction method. Just as it efficiently utilizes the materials of distance landscapes, so too does it respect and conserve the remote environments here on Earth. Those same childhood road trips to see the night sky, also exposed me to the fascinating wonders of the remote, uninhabited, and isolated deserts, mountains, and canyons of the American West. Alien landscapes at home.

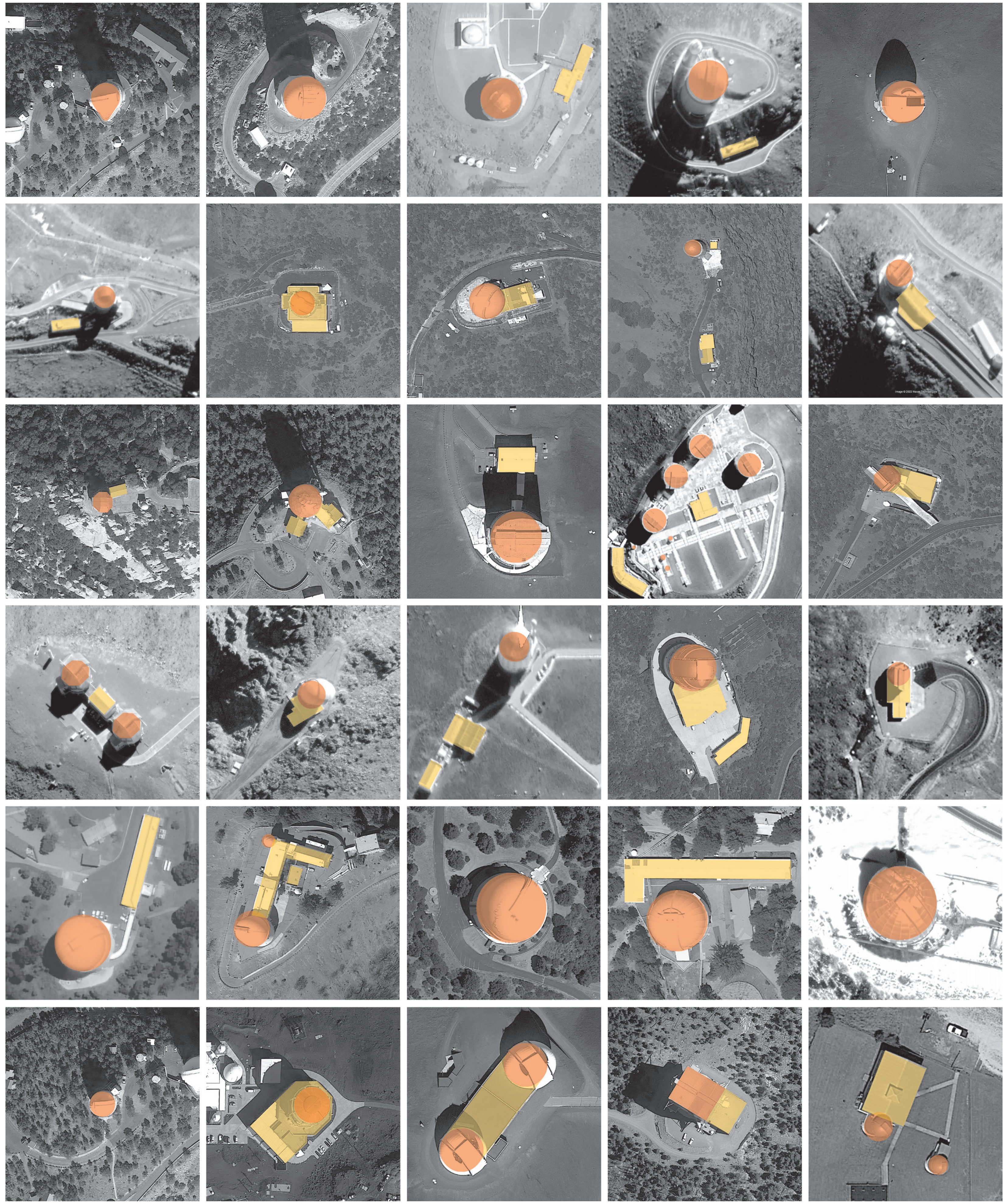
This has all culminated in this STRATA Observatory Complex. In this project I explore ideas of how the observatories of the near future might be built, how buildings in remote desert environments can be inspired by the landscape, and how the boundaries of 3D printed construction can be pushed. Someday amongst the stars, but for now here on Earth.

I am an Engineer; I seek to solve problems of the present.
I am an Architect; I seek to inspire solutions of the future.

1

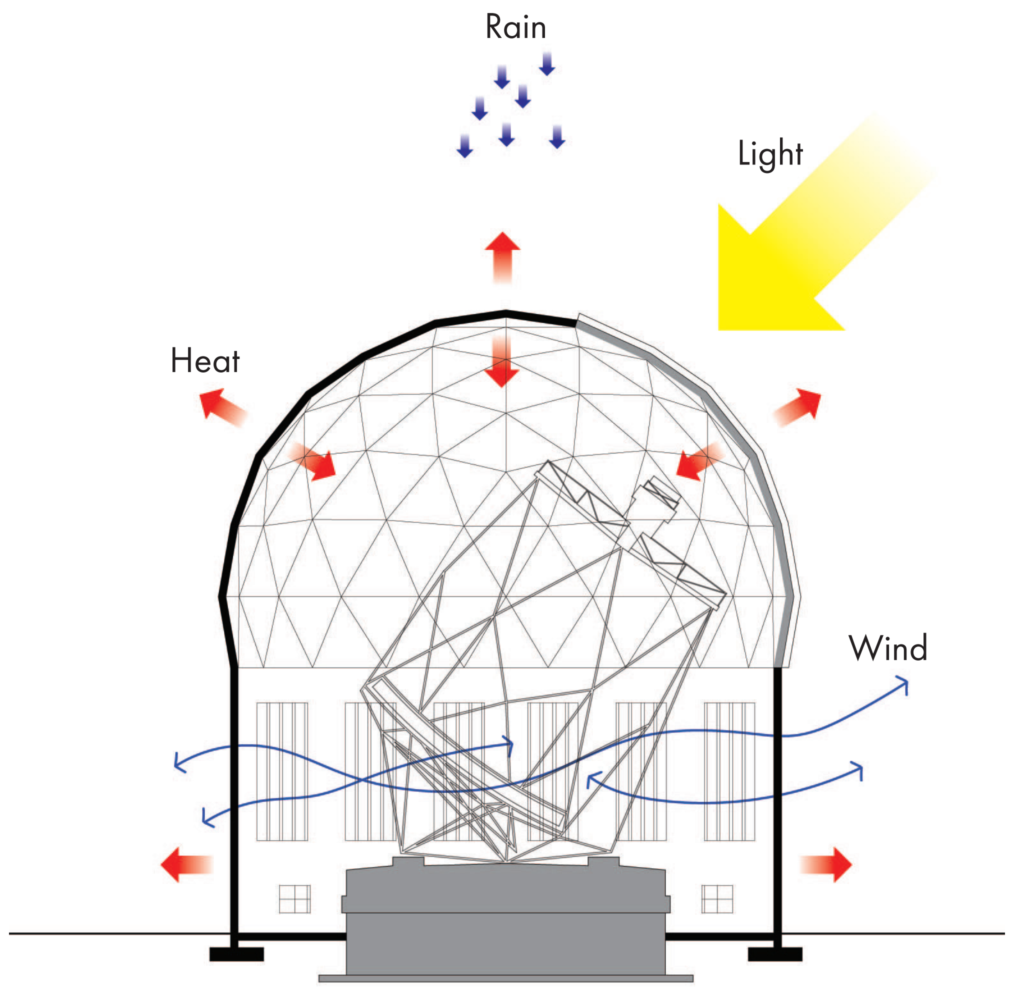
RESEARCH

The following research explores personal interests in both astronomical observatories and in 3D-printed/additive construction. Readings and precedents are used to understand the current state of each field and identify potential overlapping interests.



Observatory Building Study

Observatory Key
1. HJST
2. M4T
3. B4T
4. ESO3.6
5. CFHT
6. MPI/ESO
7. INT
8. WHT
9. NAT
10. NTT
11. WIYN
12. HET
13. SUB
14. VLT
15. TNG
16. GMT
17. SOAR
18. SALT
19. GTC
20. VISTA
21. AAT
22. LICK
23. HALE
24. MWO
25. BTA-6
26. OST
27. AEOS
28. KECK
29. LBT
30. TAMU



Dome Climate Protection Diagram

ALMA Control Room

Figure 3

Observatory Research

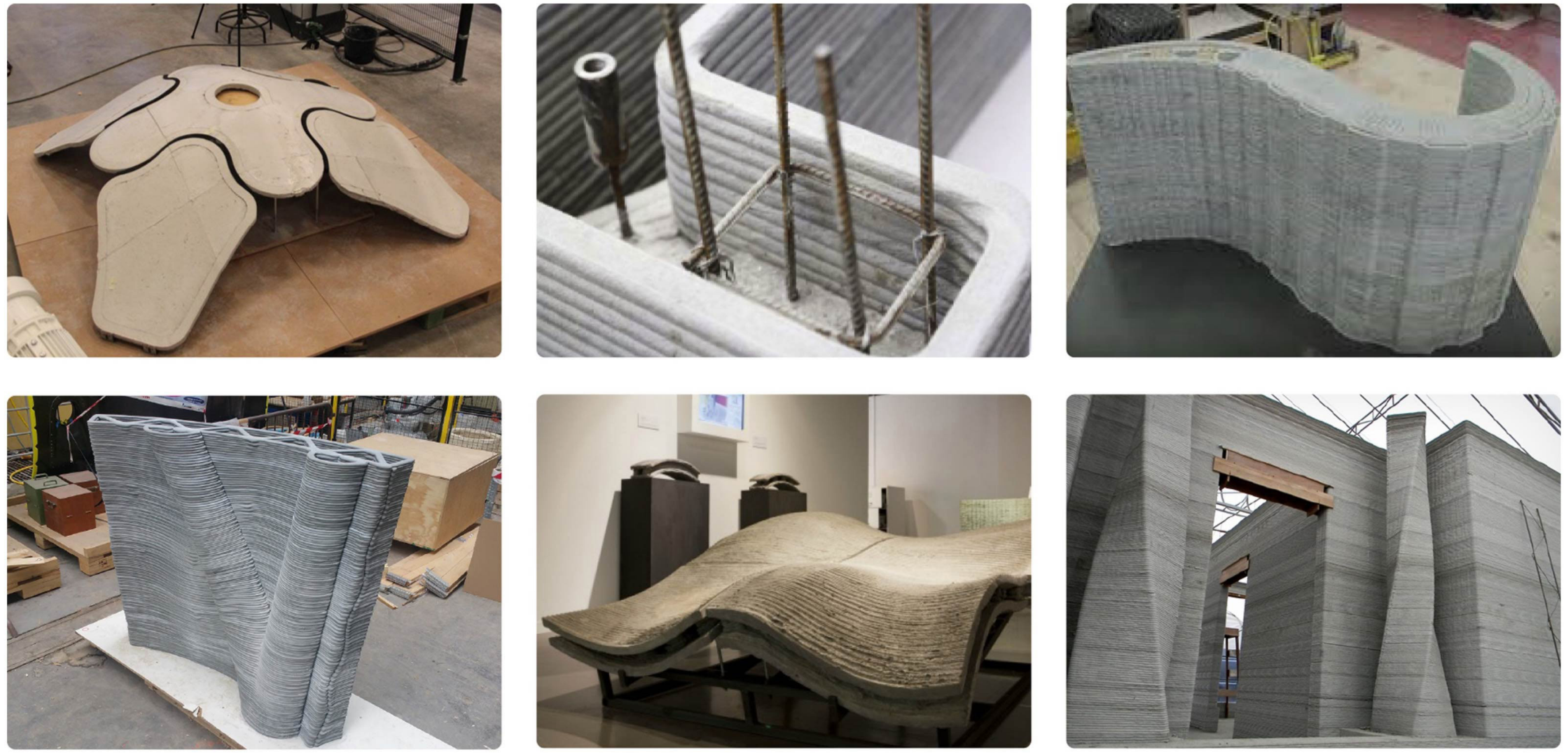
Every telescope is unique. Each is custom manufactured and finely tuned for the precise location from which it will observe the night sky. Even in the uncommon situation where sister telescopes are constructed at the same observatory or on opposite sides of the globe, the telescope and it's dome are adjusted for the local climate and position.

At its simplest, the purpose of the dome is to protect the telescope from weather and the elements while the telescope is not in operation, but to also allow for a clear viewing area while in operation. Heat from the sun, water in the form of rain, and dust on the wind can all damage telescope mirrors and motors. As such, during daylight hours the dome is sealed tight to protect the telescope, but at night the viewing doors are opened to expose the sky above.

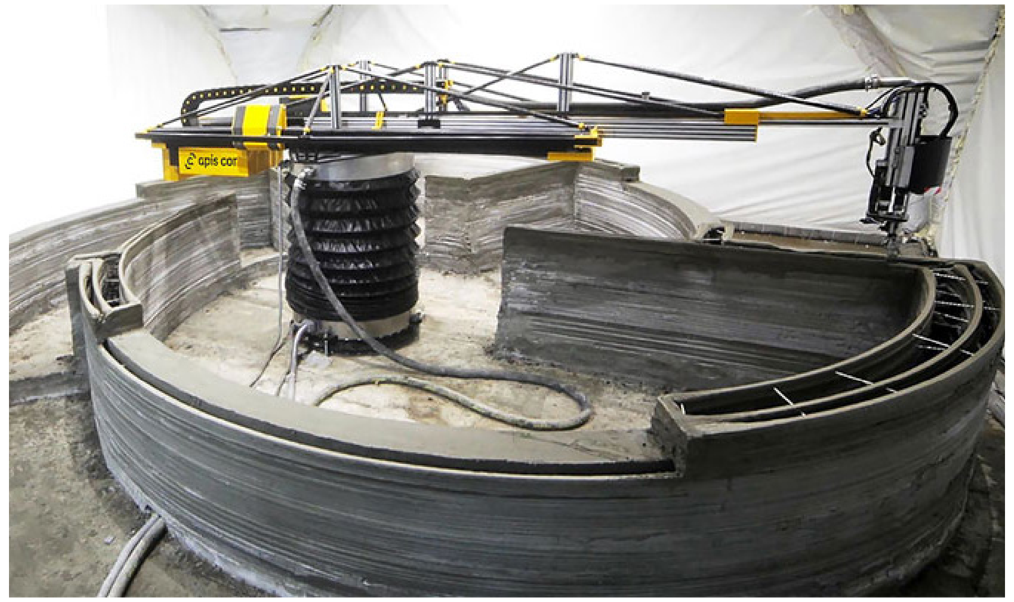
During the day, a closed dome becomes an oven, heating trapped air as the dome is baked by the sun. Furthermore, in humid climates the heat can cause condensation and even clouds to form at the top of the dome. While this quickly becomes uncomfortable for astronomers working within the dome, the added heat and humidity also prevents the proper workings of the telescope. During operation, the temperature of the telescope mirrors and the ambient air need to equalize, to reduce atmospheric lensing effects. Ventilation in the walls of the dome allows the release of hot or humid air on the breeze, and in extreme situations the viewing window can be opened.

The control room imagined by many, the large room housing enormous computers with reactor-style desks, has quickly become a thing of the past. Modern observatory control rooms are open spaces with multiple seats from which a controller can work from their laptop. Many telescopes are now accessed and controlled completely remotely over the internet, with on-site employees focused on day-to-day maintenance and upkeep.

The size of modern telescopes is trending larger. A race is underway to build the largest telescope. The increase in telescope size, support spaces, and communication infrastructure results in ballooning up-front costs, and many smaller institutions are unable to afford such a steep initial investment. As such, modern observatories are almost exclusively owned by the largest governments and universities, leaving behind much of the scientific community.

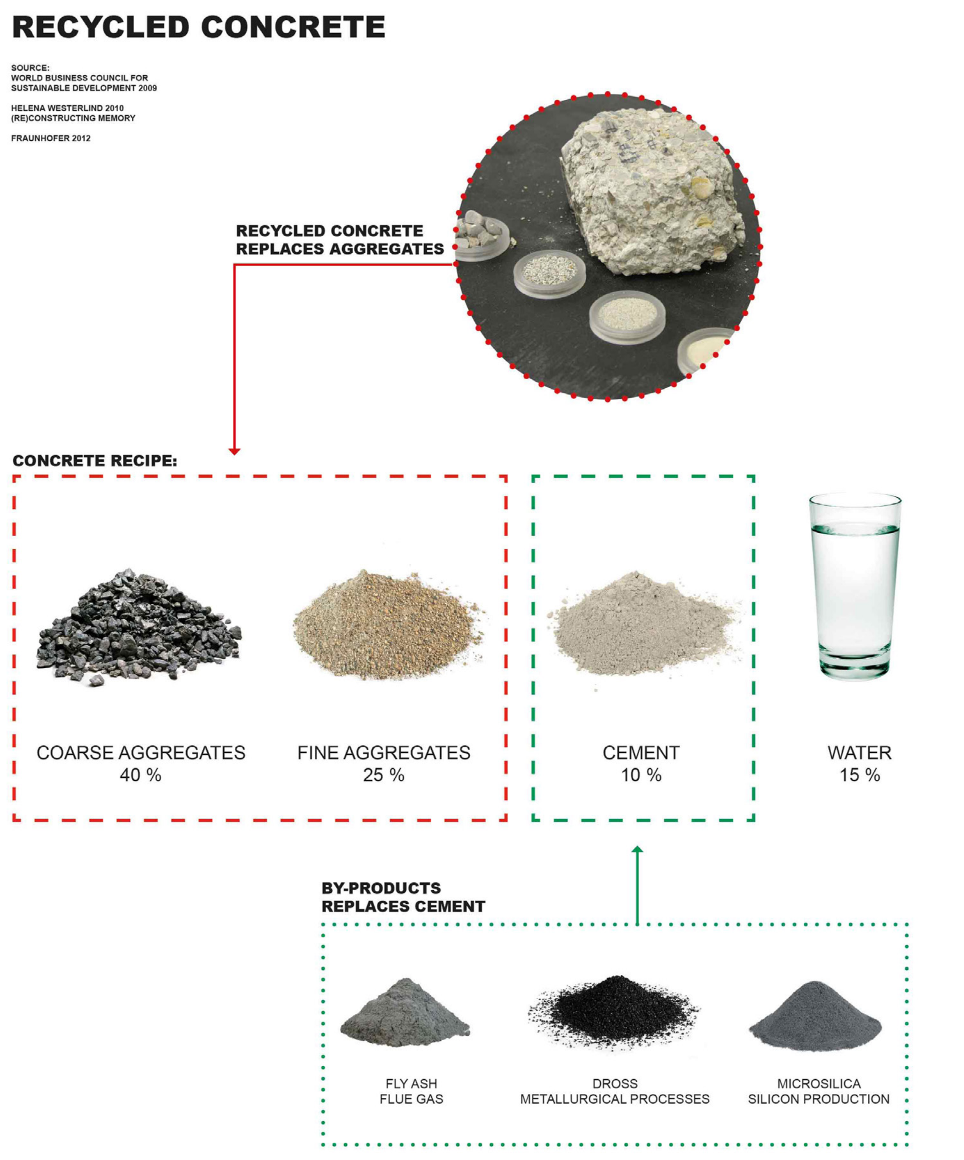


3D Printed Concrete Methods Figure 4

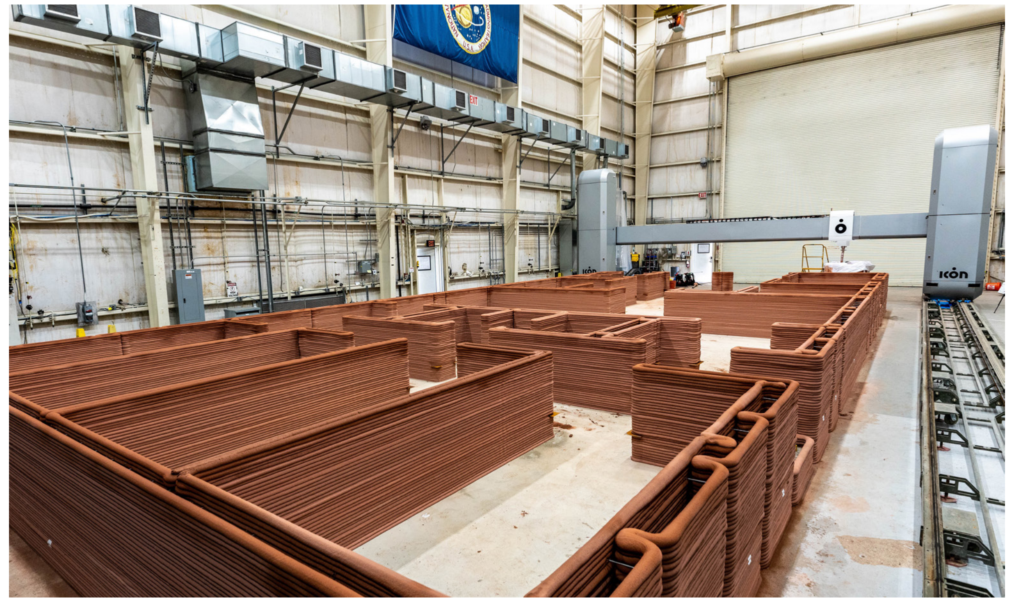


Apis Cor Radial 3D Printer Figure 5

ICON Conveyor Belt 3D Printer Figure 6



Average 3D printer concrete mixture contents *Figure 7*



ICON Simulated Mars Surface Habitat for NASA *Figure 8*

3D Printing Research

Once a novelty, 3D printing looks to be a key player in the future of architecture and construction. The method has been used for two decades for toolmaking and prototyping. While initial inroads to construction were slow, recent innovations in scale and transportation have led to an explosive growth for 3D-printed construction. Also known as additive construction, 3D printed construction can create walls for full-size buildings out of concrete, clay, or other earthen materials.

Quite different from traditional construction, 3D printed construction has many strengths and weaknesses, and is still in its infancy as a construction method.

Pros:

Speed: Current 3D printing construction projects have shown that they are capable of producing a full home in a matter of days, significantly faster than other construction projects of comparable size.

Reduced Material Waste: As an additive construction method, 3D printing only uses the material needed, reducing the amount of construction waste to near zero.

Design Freedom: Because the process is computerized, complex forms that would otherwise be labor-intensive or impractically precise are now accessible to architects and designers.

Reduction in Labor: The computerization of the construction process means that significantly fewer laborers are required to manufacture a full building, a particularly important benefit as the construction industry faces a large labor shortage.

Cons:

Higher Costs, Currently: The nature of an emerging technology means that prices are high until mass adoption and availability drives costs down. At the moment the potential cost savings are not yet realized.

Limited Size: Current 3D printers are larger than they have ever been, but they still have trouble printing anything larger than a small house. Furthermore, the material science limitations at the moment prevents multi-story loads or tall, unsupported spaces.

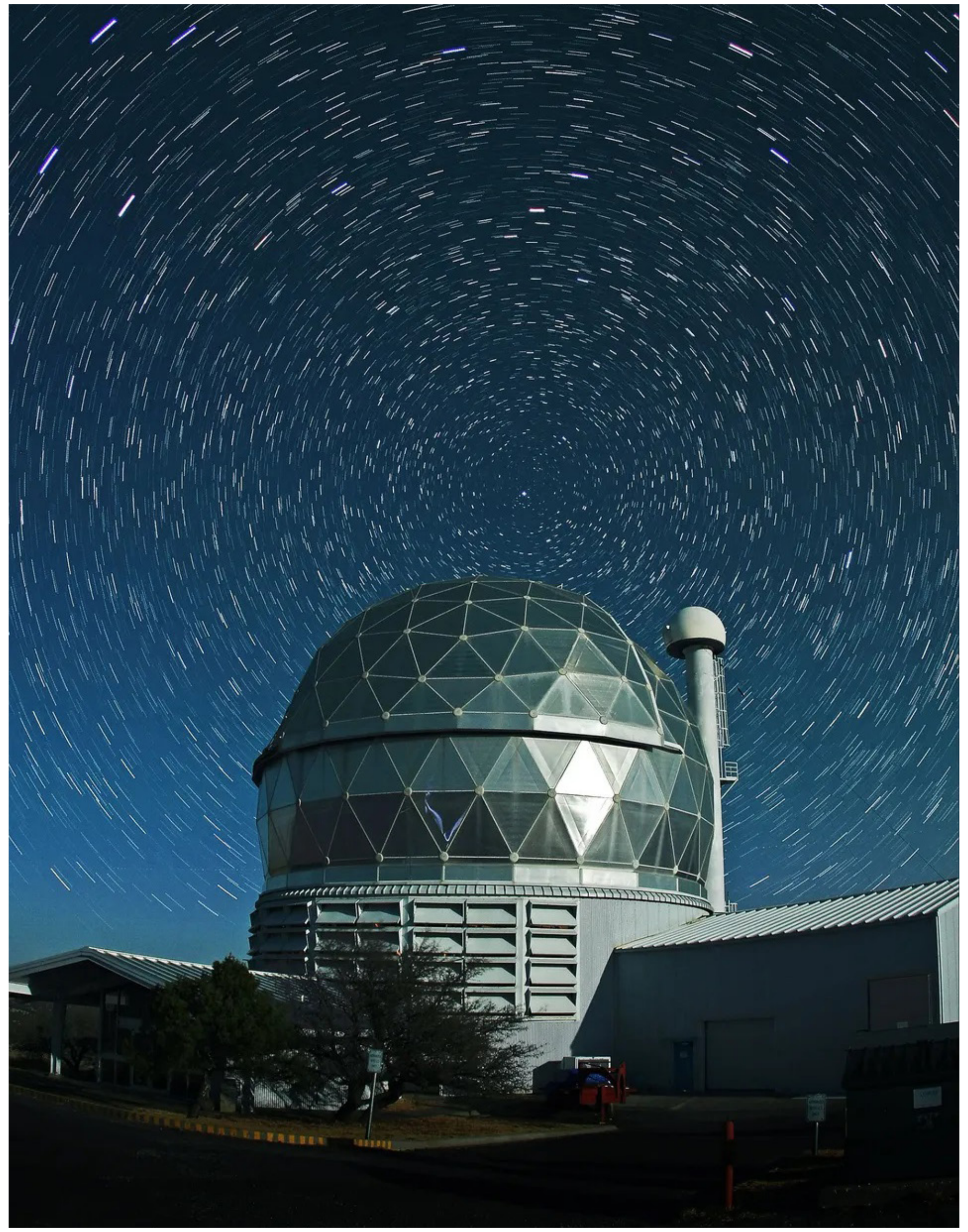
Increased Laborer Skill: While fewer laborers are needed, those few laborers need to have significantly more technical skill to operate and oversee 3D printers.

Regulation Challenges: 3D printing has yet to be tested in many jurisdictions, and often it is vague how those codes apply.

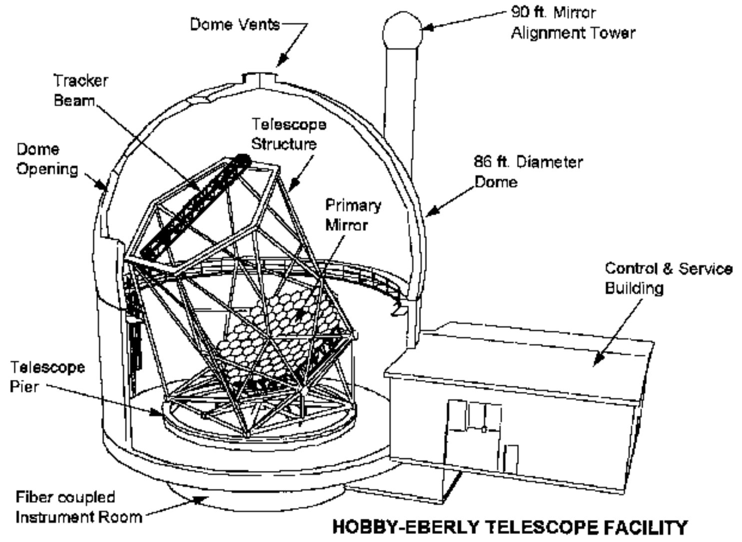
Hobey-Eberly Telescope *Figure 9*

Hobey-Eberly Telescope *Figure 10*

Hobey-Eberly Telescope Cut Showing Telescope *Figure 11*



Night Sky Over the Hobby-Eberly Dome *Figure 12*



Hobby-Eberly Telescope and Dome Components *Figure 13*

Hobby-Eberly Telescope (HET)

University of Texas
1996
Research
McDonald Observatory, Davis Mountains, Texas

The Hobby-Eberly Telescope (HET) first began imaging the sky in 1996, with updates completed in 2016. With a diameter of 10m (~32.8ft), the HET is one of the largest optical telescopes in the world. The geodesic sphere that makes up the roof of it's dome is 86ft in diameter, while the lower cylinder is approximately 80ft in diameter. Part of the McDonald Observatory system, the telescope is operated by the The University of Texas at Austin, in partnership with universities from around the world.

The HET is an early pioneer of the method of using segmented primary mirror. Hexagonal mirrors, 91 of them, are arranged to focus light to a focal point, in the same way as a concave mirror lens would. The benefit is that each mirror can be adjusted, cleaned, and replaced independently, significantly reducing the cost of the telescope mirrors. This method has become the new standard for both terrestrial and orbital telescopes worldwide.

This segmented mirror system is paired with a fixed elevation axis. The telescope itself can only spin about its vertical axis; it cannot tilt up or down. Instead, it uses an innovative tracking system to angle each of the segmented mirrors independently to move the focal point across the night sky, often using only a portion of the mirror array at any given time. These telescope methods reportedly reduced the cost of construction of the telescope by 80% compared to other optical telescopes of a similar size. This highlights just how large of a priority managing initial investment costs is to observatory construction.

Support functions for the telescope and dome consist of maintenance rooms, offices, and a visitor center space located in windowless rectangular metal buildings adjacent to the dome.

The HET set the bar for a generation of ground based optical telescopes. This telescopes once novel techniques are now the industry norm, and it's innovative spirit continues in every telescope built since.

VLT at Paranal Observatory *Figure 14*

VLT at Paranal Observatory *Figure 15*

VLT at Paranal Observatory *Figure 16*

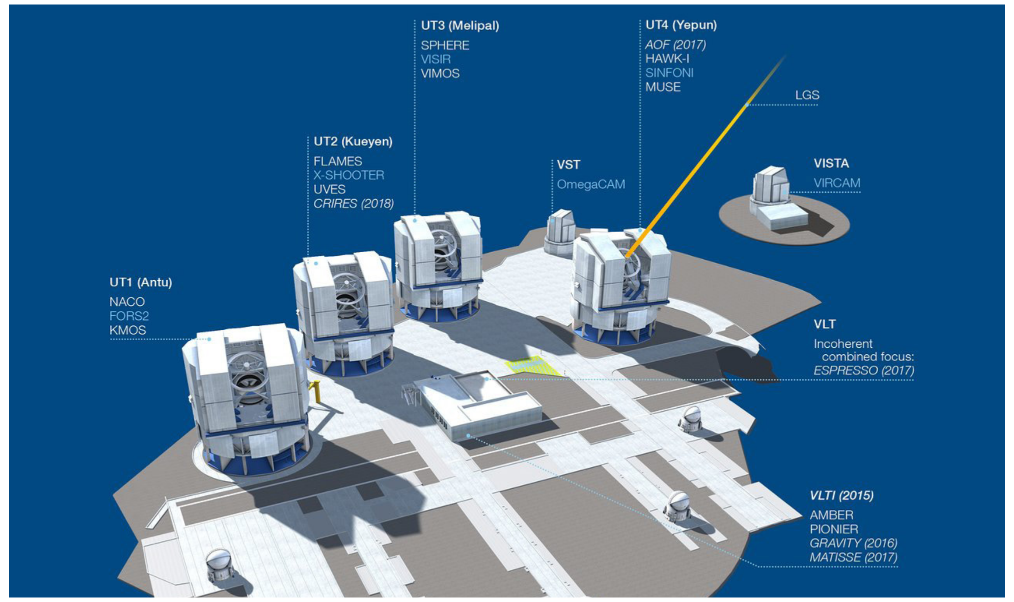


Diagram of VLT Unit Telescopes *Figure 17*

VLT at Paranal Observatory *Figure 18*

VLT at Paranal Observatory *Figure 19*

Very Large Telescope (VLT)

ESO
2022
Research
Paranal Observatory, Chile

The Very Large Telescope (VLT) is, as the name would imply, one of the largest telescopes in the world. Located on Cerro Paranal in the Atacama Desert of northern Chile, the VLT is one of many observatories operated by the European Southern Observatory (ESO).

The VLT is a bit less tangential than most telescopes. Physically, the VLT consists of four individual Unit Telescopes (UT), named Antu, Kueyen, Melipal and Yepun. The four UTs each have 8.2 meter lenses and are equipped to view in both the visual and infrared light ranged. Each telescope operates independently, allowing astronomers to observe multiple targets at once.

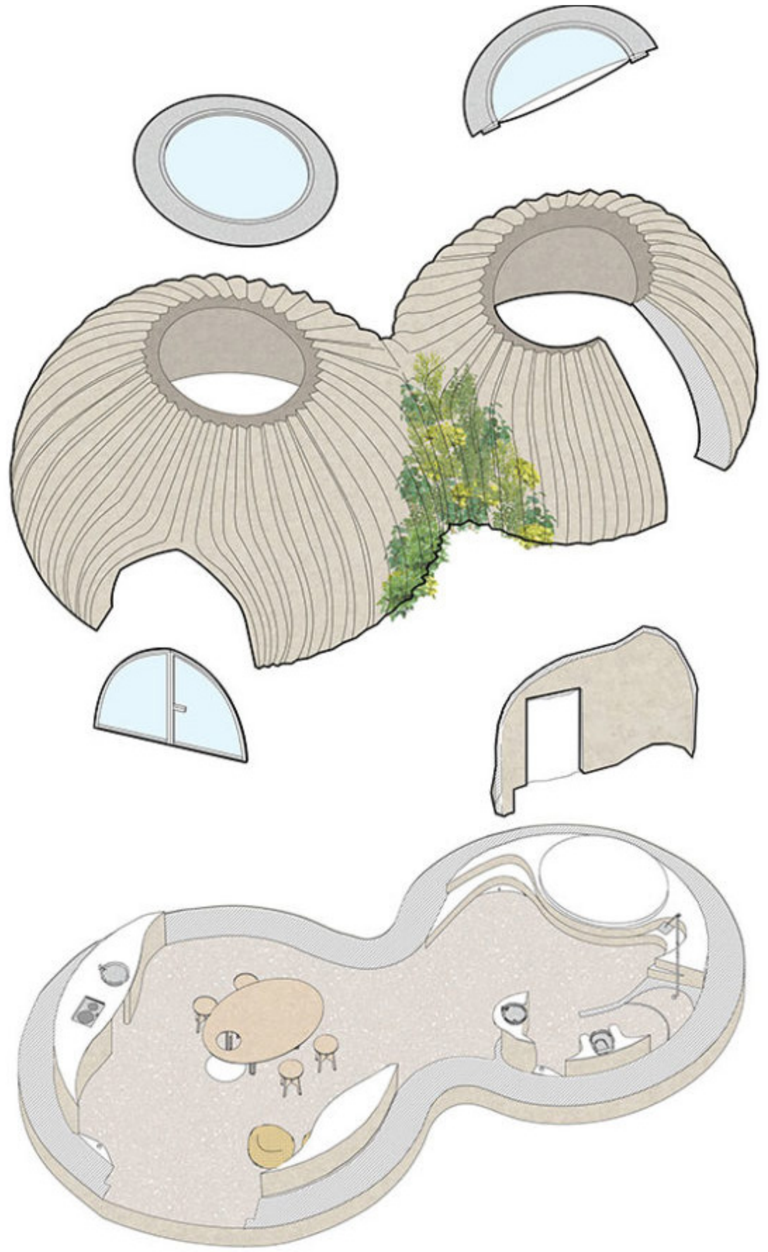
The real power of the VLT emerges when the UTs work in conjunction. When aimed at the same target, a larger telescope is digitally created in the aggregate. This method, known as an astronomical interferometer, creates an image with higher angular resolution as if it was taken from a larger telescope.

A secondary benefit of multiple sister-telescopes, is that controls and maintenance for each telescope is the same. This reduces costs, and well as streamlining operations.

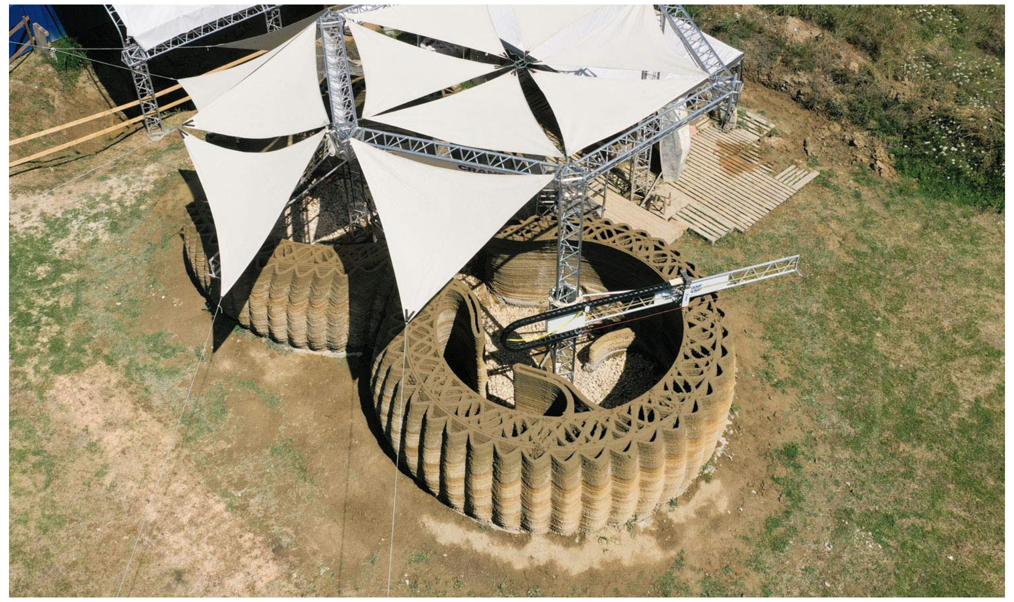
TECLA Elevation Figure 20

TECLA Interior Render, Day Figure 21

TECLA Interior Render, Night Figure 22



TECLA Exploded Diagram Figure 23



TECLA Construction Figure 24

TECLA

WASP, Mario Cucinella Architects
2021
Research, Home
Massa Lobarda, Italy

A full scale prototype, TECLA is intended to be one of many. Designed by Mario Cucinella Architects, and printed by WASP, TECLA aims to be an innovative habitat that takes full advantage of newly available technology.

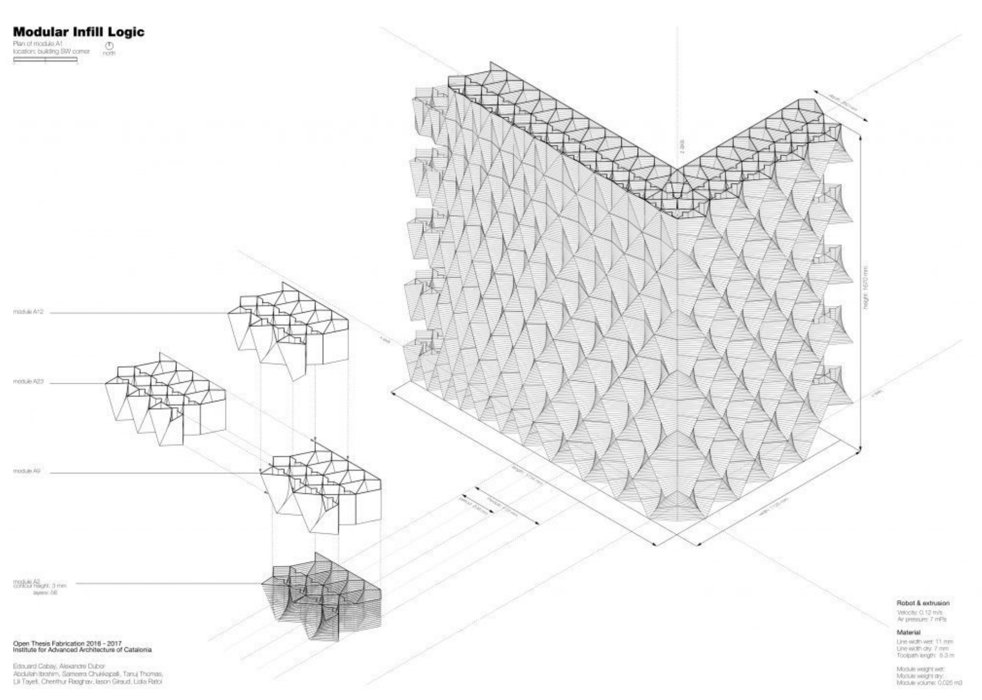
The circular house is created of entirely reusable and recyclable materials, the majority of which is the locally sourced clays that make up the 3D printed walls. This use of the local soils is intended to change with the location. Should the home be constructed elsewhere, the local materials will change the very make-up of the building, affecting the color, texture, insulation properties, and structural capabilities. TECLA gets its name from the use of local soils, as TECLA is derived from the works technology and clay.

TECLA's double dome design allows the walls to fill the rolls of structure, roofing, and cladding all in one. This unifies these multiple aspects into a single high-performance home.

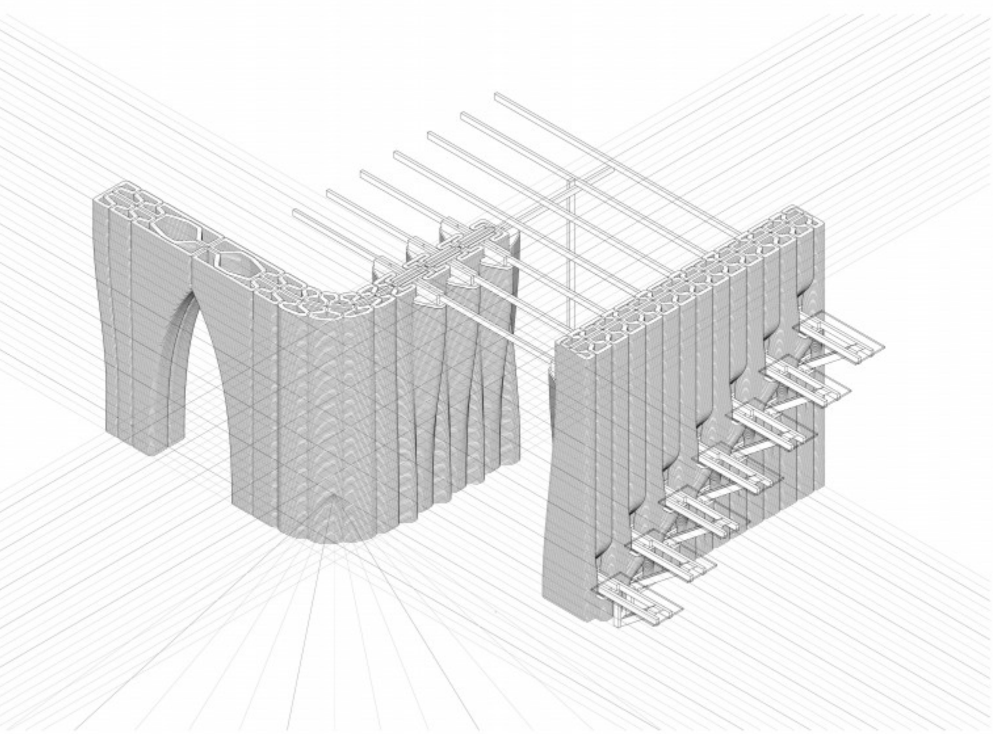
WASP fully intends for this to be a project that is easy to duplicate and modify. Taking advantage of the digital nature of 3D printing, moving the crane to a new location is all that is needed to reproduce the structure. Similarly, scaling the building or adding a third dome is as easy as the press of a few buttons. WASP envisions a site with multiple variations of this building creating a community of homes, gardens, and workshops.

TerraPerforma *Figure 25*

Building Architecture Continuity *Figure 26*

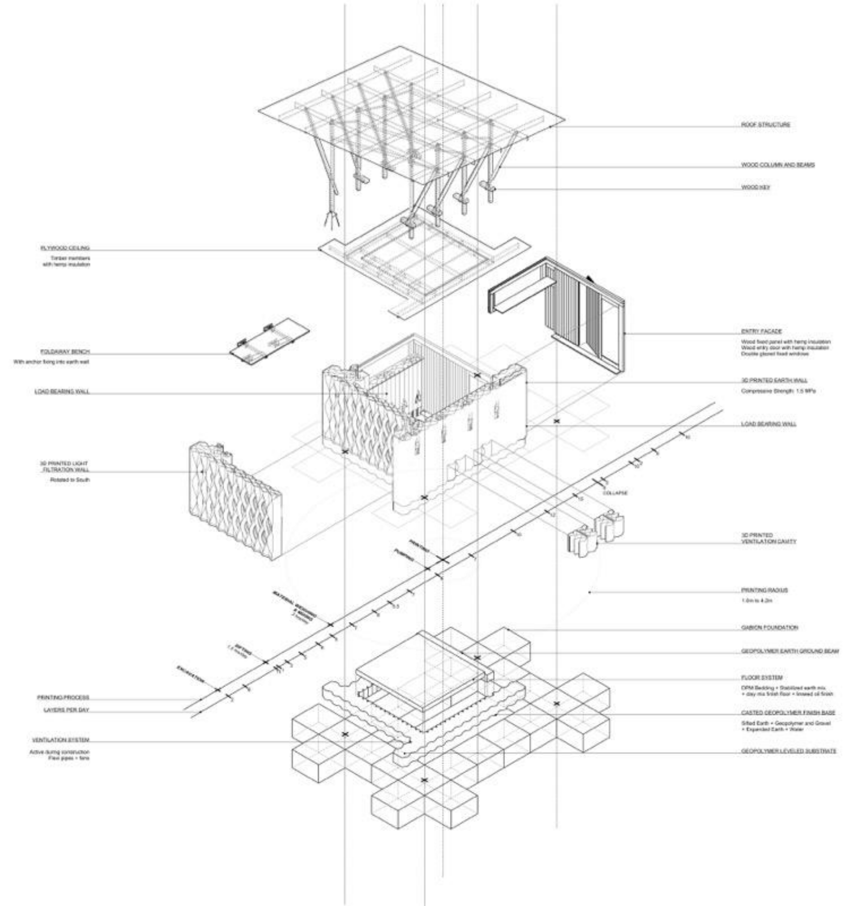


TerraPerforma Diagrams *Figure 27*



Building Architecture Continuity Diagram *Figure 28*

TOVA *Figure 29*



TOVA Diagram *Figure 30*

1: TerraPerforma

IAAC
2016/2017
Research
Barcelona, Spain

2: Building Architecture Continuity

IAAC, WASP
2019
Research
Barcelona, Spain

3: TOVA

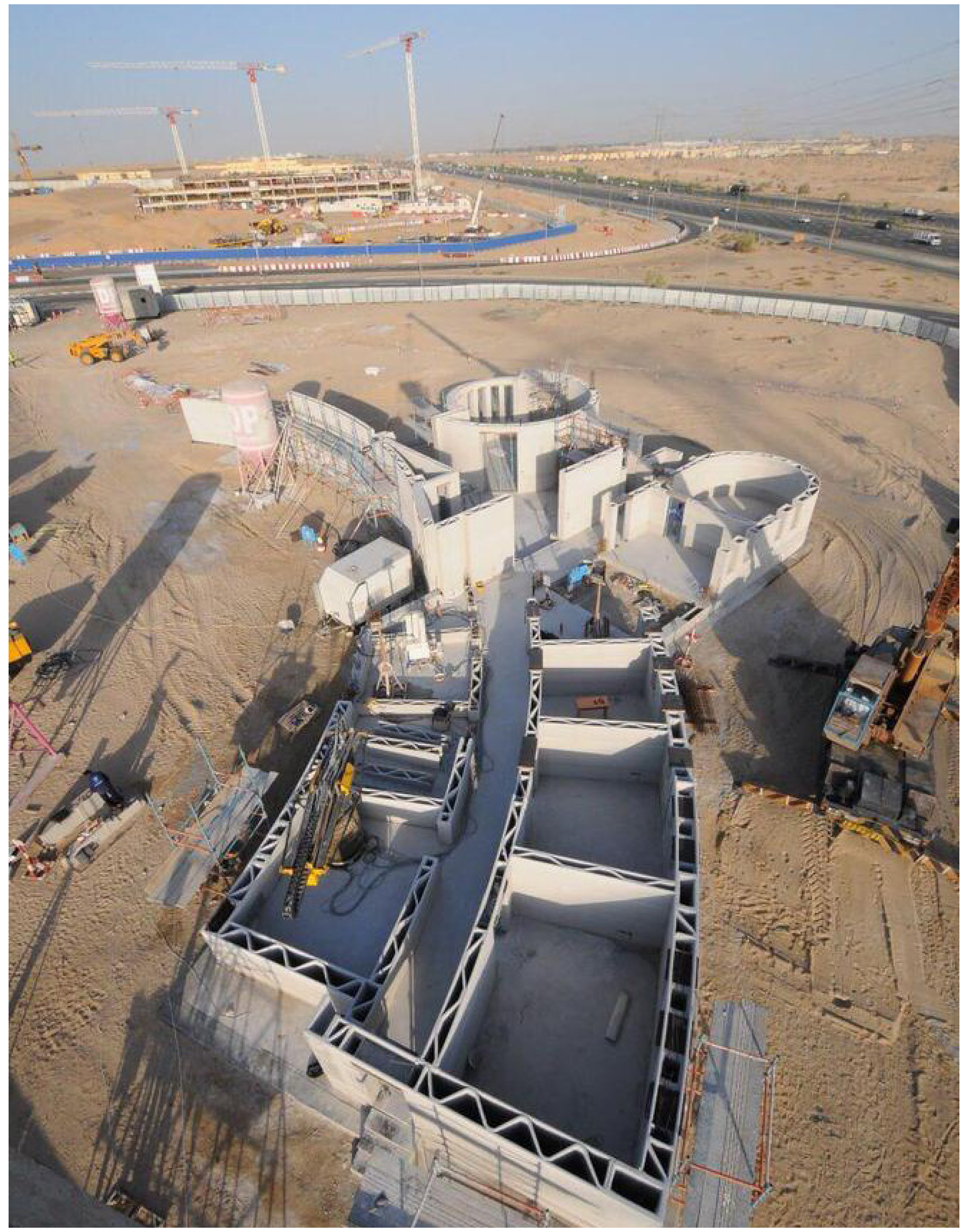
IAAC, WASP
2022
Research
Barcelona, Spain

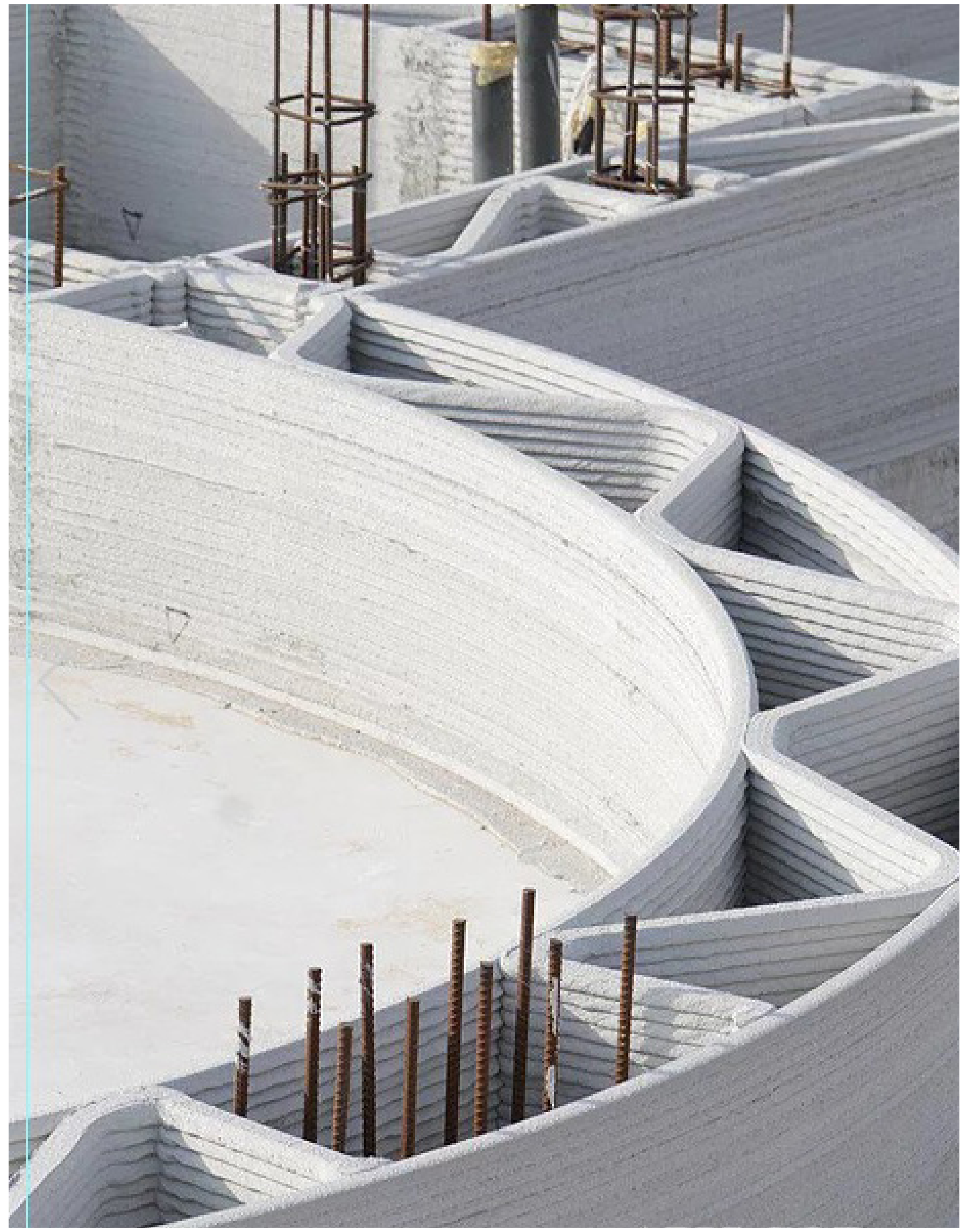
These projects are each student work, completed as part of the Institute for Advanced Architecture of Catalonia's (IAAC) Open Thesis Fabrication (OTF) program. Completed in different years, by different student, these projects use different mixes and printers, but the idea of challenging the limits of a 3D printed wall carries through each project.

TerraPerforma embraces the rapid manufacturing capabilities of 3D printing to create custom hollow clay blocks, which are then stacked to form the walls. The project primarily questions how the wall form can be altered to shade itself, reducing heat gain from sunlight. The clay material is similarly chosen for it's thermal properties.

Building Architecture Continuity explores the integration of circulation elements into the built fabric of the walls. Doorways, windows, stairs, and floor supports are seamlessly melded into the wall surface, creating a smooth, continuous structure.

TOVA is the first fully 3D printed building completed by IAAC, and is primarily concerned with it's impact on the environment. Designed to minimize waste, TOVA is constructed using methods picked up from their partnership with WASP, particularly the use of local materials in the clay mixture used for the walls.


Dubai Municipality Building Construction *Figure 31*


Dubai Municipality Building Construction *Figure 32*


Dubai Municipality Building Construction *Figure 33*


Dubai Municipality Building Unfinished Interior *Figure 34*


Dubai Municipality Building Elevation *Figure 35*


Dubai Municipality Building Elevation *Figure 36*


Dubai Municipality Building Elevation *Figure 37*

Dubai Municipality Building

Apis Cor
2022
Government
Dubai, United Arab Emirates

Currently the largest 3D printed building in the world, the Dubai Municipality Building challenges all ideas of scale of a 3D printed building. The building has a footprint of 640 square meters (a little more than 6800 square feet), and is one of a very small number of two-story 3D printed buildings.

To overcome the scale limitations of the current 3D printed construction methods, the Dubai Municipality Building and Apis Cor adopted a more mixed construction method. The 3D printed walls are reinforced with rebar columns and traditional cast-in-place concrete. The floors and roof are constructed of precast concrete slabs, bearing on the walls.

A major test of Apis Cor's equipment, this construction project shows that their printing equipment can operate in the hostile desert in which they were building. With no humidity or temperature control, the robotics and gypsum-based concrete mixture both held up without any trouble.

2

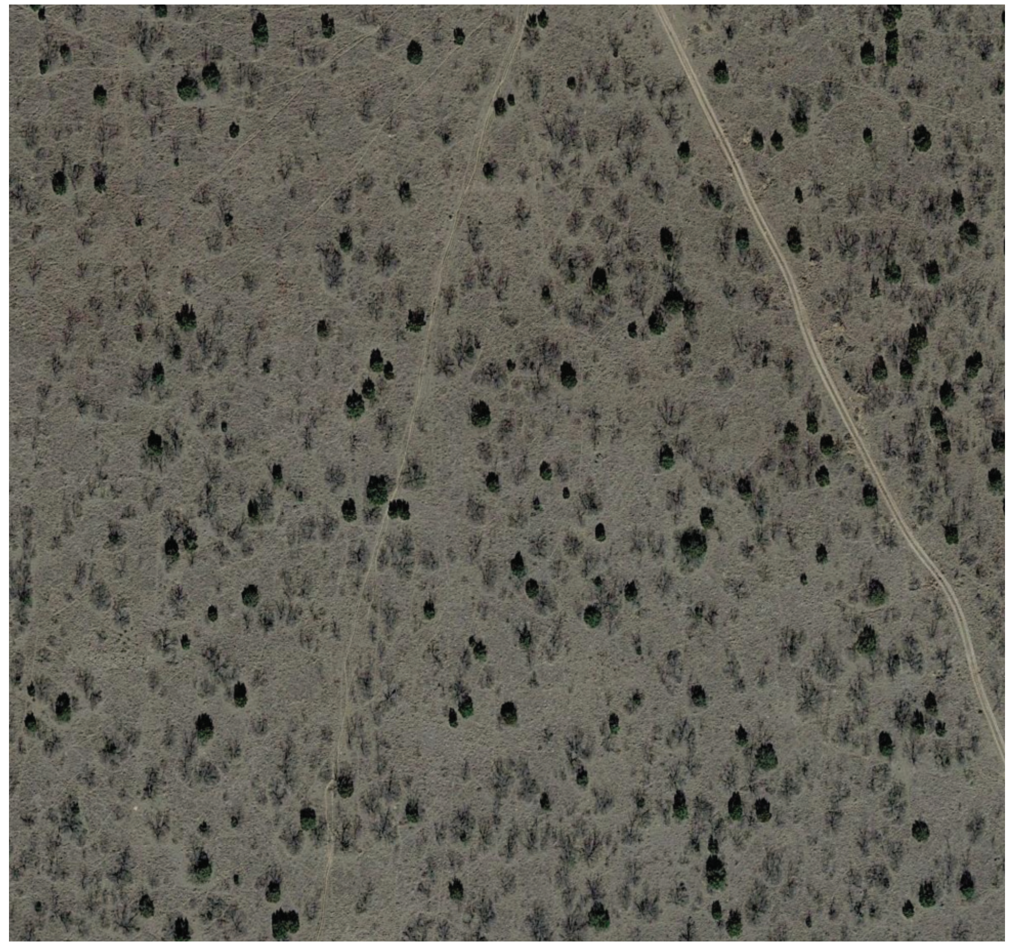
SITE & CLIMATE

The following chapter examines the site, and the climate in which it is located. Weather, visibility, natural terrain features, and other factors are identified as contributing and controlling elements.


1: Satellite Imagery Figure 38


2: Satellite Imagery Figure 39


3: Satellite Imagery Figure 40


4: Satellite Imagery Figure 41

Site Location

Located in Armstrong County, TX, the project is in the very heart of the Texas Panhandle. Surrounded on three sides by Palo Duro canyon, the site is within a half-mile of the canyon edge.

The surrounding area is very sparse. Currently used as ranch land, the site is sparsely populated with bushes and short trees. A few dirt roads currently criss-cross the property, created as a result of ranchers patrolling their fences.

The remoteness of the site is ideal for an observatory. The lights of the nearest big city, Amarillo, are flat against the horizon. The flat terrain means that there are no natural obstructions blocking views in any direction.

The off-the-grid nature of the site means that utilities would have to be added, but solar panels, wind turbines, and/or rainwater collection could all be added to support the site and reduce the project's costs and environmental impact.


Texas, United States Figure 42


Armstrong County, Texas Figure 43

Palo Duro, Lighthouse rock in the background, Rocky Mountain juniper trees in the foreground Figure 44

Panorama of Palo Duro Figure 45

Palo Duro Carves the Plains Figure 46

Roadrunner in Palo Duro Figure 47

Playa Lake Figure 48

Palo Duro Canyon

Known for its beautiful colors and stunning views, Palo Duro Canyon is a popular tourist destination in the panhandle of north Texas. Extending 120 miles, Palo Duro Canyon is the second largest canyon system in America. Four distinct geographic layers exist in the canyons 800ft walls, dating back 250 million years into Earth's history.

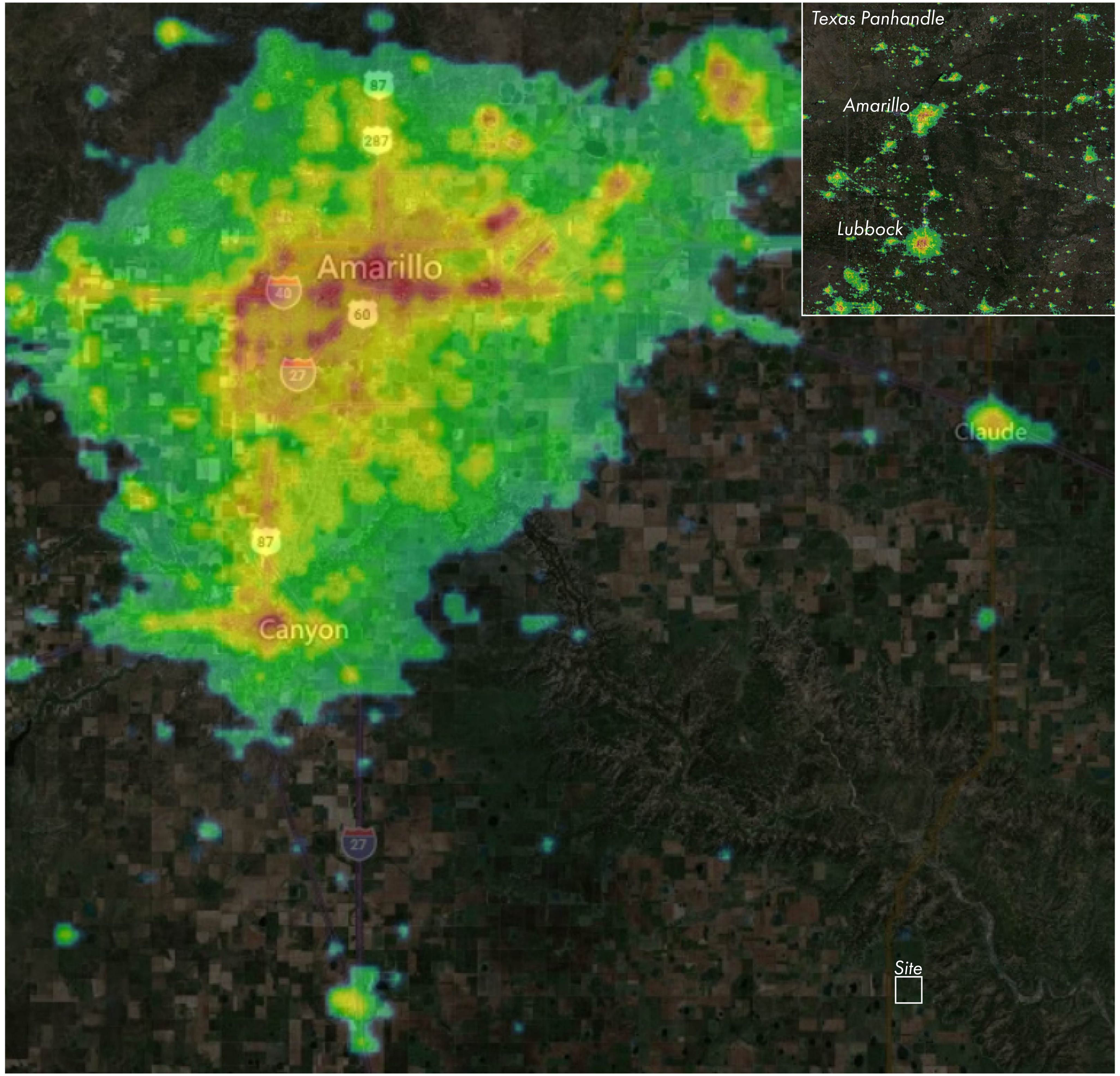
Popular with tourists and wildlife, the canyon's green foliage creates an oasis and unique habitats. It is from this greenery that the canyon gets its name. palo duro means 'hard wood' in Spanish, a reference to the Rocky Mountain juniper trees found throughout the canyon.

The most recognizable feature in the canyon, the Lighthouse rock is an isolated hoodoo that looks over the canyon. Fairly easily accessible on foot or bike, the Lighthouse is one of the most visited and photographed locations in the park, with the canyon's geographic history on full display.

The canyon creates a pocket of green habitat that sustains a wide range of animal life. Common residents include wild turkeys, white-tailed and mule deer, coyotes, bobcats, roadrunners and many species of snakes and lizards. The canyon is also home to two endangered animals, the Texas horned lizard and the Palo Duro mouse, the latter of which is only found here.

Move above the canyon rim and the world changes. The steep topography that defines the canyon is replaced with extreme flatness. The canyon walls no longer shade from the sun or block strong winds that roll across the plains. The lack of year-round access to water and the thick layer of clay under the soil make this poor farmland, but the wide spaces make ideal ranch land.

When it does rain, the water that falls here has nowhere to go. It collects in temporary lakes, known as playas, averaging 15 acres in size. These large puddles evaporate in the heat or slowly seep into the ground, until after a month or so nothing is left but a dry mud bed. This natural phenomenon is at its largest concentration in north Texas with 19,300 playas found in the Texas High Plains.

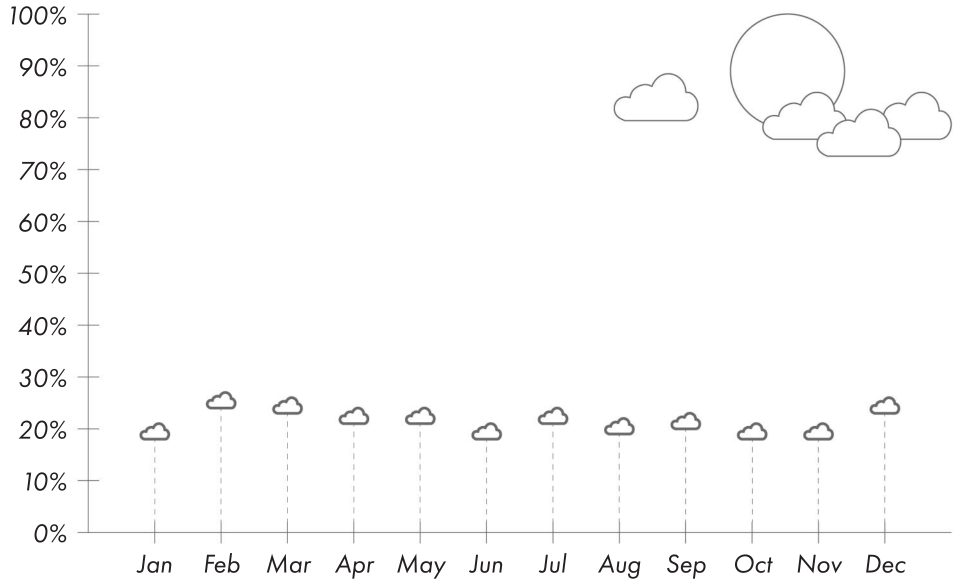


Dark Sky Map

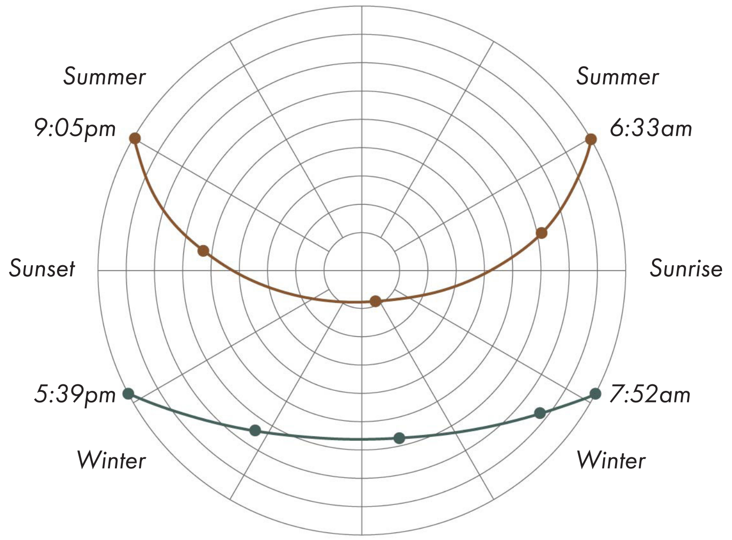
Figure 49

Milky Way over the Lighthouse

Figure 50



Average Monthly Cloud Cover



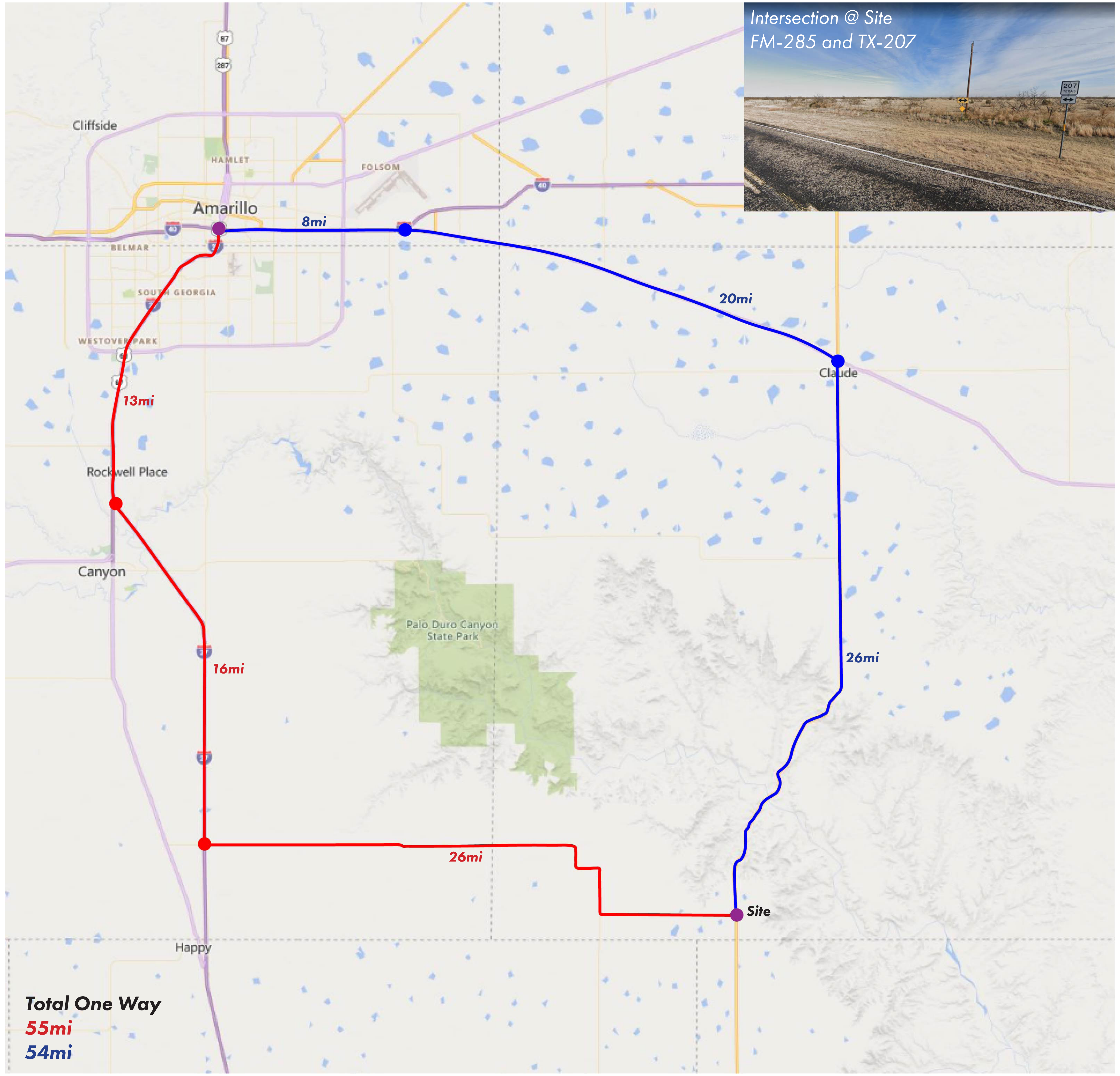
Sun Path

Dark Sky

Because the purpose of an optical telescope is to image trace sources of light in the night sky, any other sources of light can completely ruin the work astronomers produce. As such, locations with a clear night sky, far from large cities, are chosen for observatories.

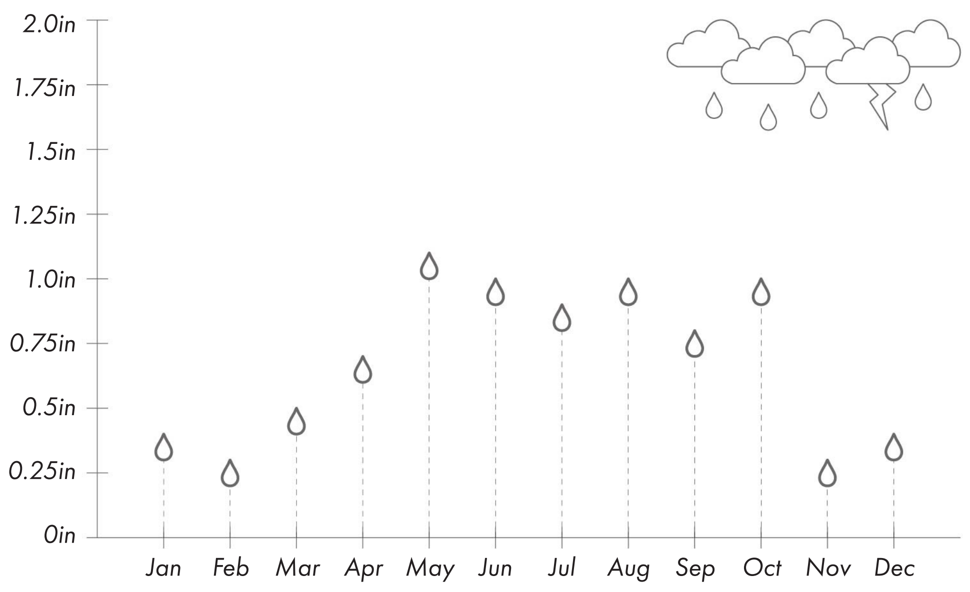
When designing an observatory, the dimensions of the dome and telescope are carefully designed to maximize how much of the night sky is viewable. As light-pollution becomes an ever-increasing problem, viewing the sky just above the horizon becomes impossible, and many newer telescopes forgo trying to image the potion of the sky just above the horizon. Many do not even have the capability to lower the telescope to the horizon line. The area around Palo Duro is ideal when it comes to avoiding light pollution. The area is only lightly populated, is far from the main sources of light pollution, and the State Park is intentionally kept naturally dark.

In addition to light pollution, cloud cover can block the view of the night sky and make imaging impossible. For this reason, relatively dry locations with historically few cloudy nights are considered when placing an observatory. The panhandle of North Texas meets both considerations. The low rainfall and fast winds keep the sky clear of lingering cloudy days. The unobstructed plains mean that and clouds cover that does form is quickly pushed along, blown away by the currents.

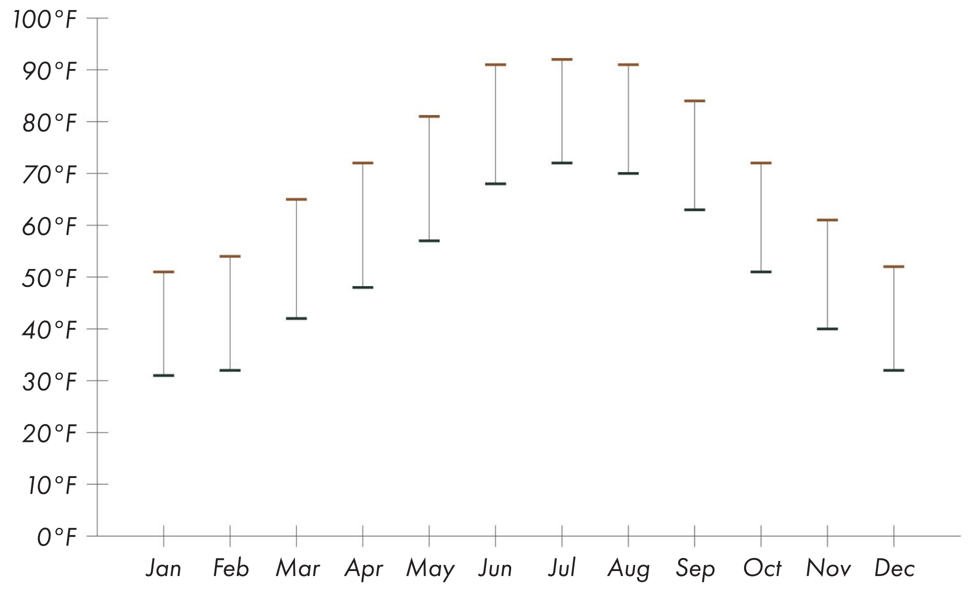


Travel Distances from Amarillo to Site

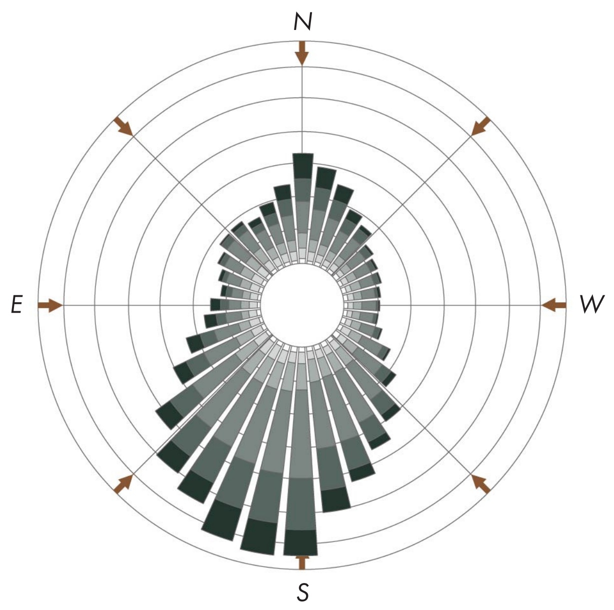
Figure 51



Average Monthly Rainfall



Average Monthly Temperature



Wind Rose

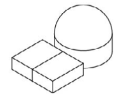
Travel

A defining feature of the chosen site is it's remoteness. While this in intentional for ideal operations of the telescopes, its had the unfortunate side-effect of increasing travel distance and time to the site. Every additional trip to the site, both for materials and laborers, adds to the financial and environmental cost.

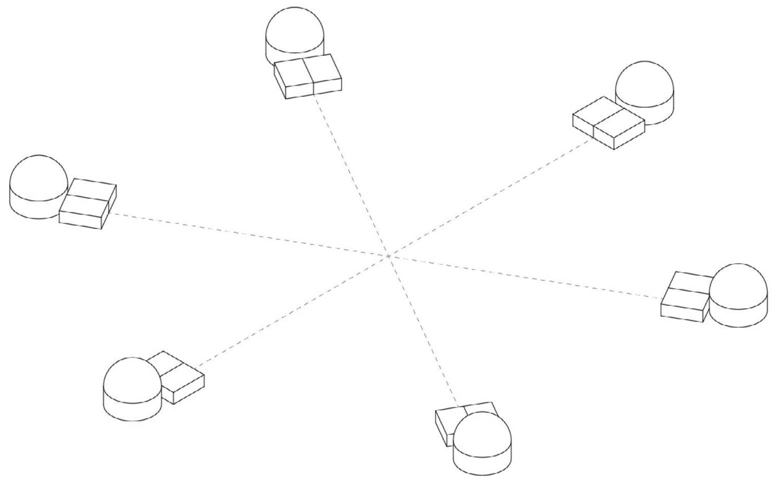
3

DEVELOPMENT

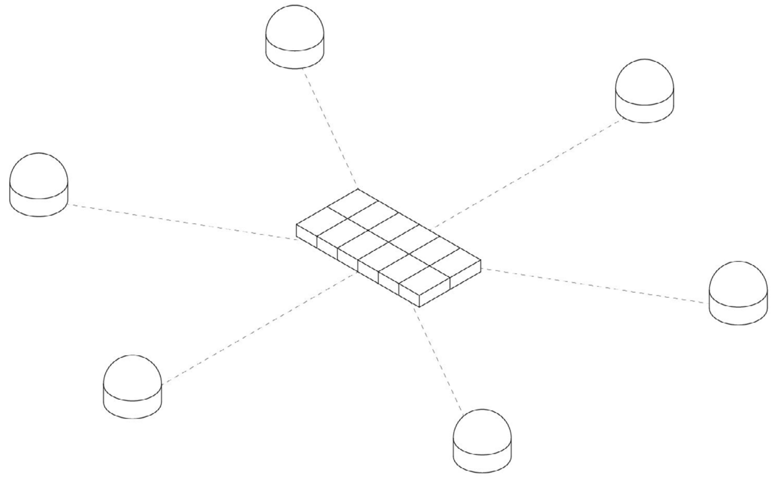
The following chapter covers the development of the project from program and parti to completed design drawings. Plans, sections, elevations, and renders showcase the project goals.



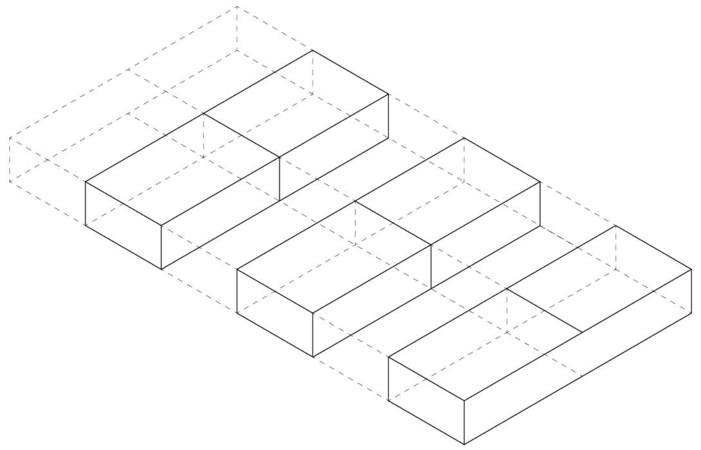
1 Dome Massing



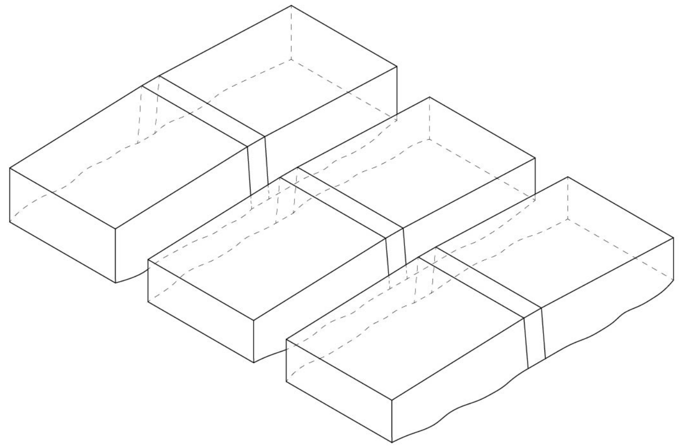
2 Radial Duplication



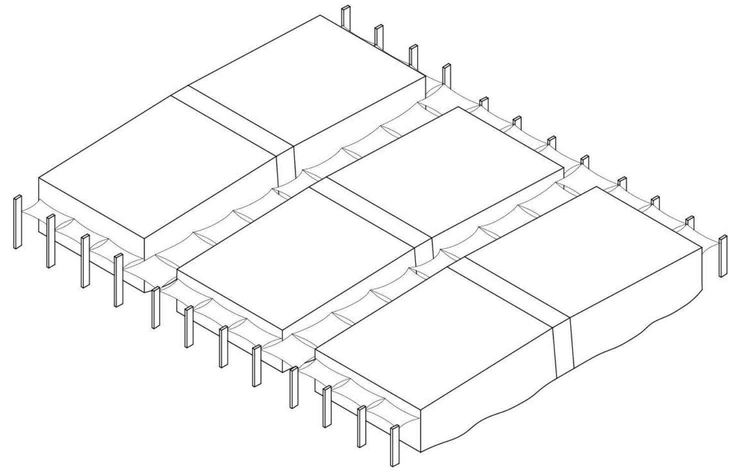
3 Centralize Support



4Eliminate Duplicate Spaces



5 Add Canyon Walls



6 Shade Canyons

Parti, Program, and Goals

PROGRAM TABLE

FUNCTION	AREA SF.FT	#	TOTAL AREA
DOME			
Telescope	5,026	6	30,156
			30,156
OFFICE			
Open Office	1,770	2	3,540
Office	150	4	600
Storage	120	4	480
Meeting	240	3	720
Kitchen/Lounge	240	1	240
Restroom	80	2	160
Patio	540	2	1,080
			6,820
CONTROL			
Control Room	2,550	2	5,100
Meeting	240	1	240
Kitchen/Lounge	240	1	240
Restroom	80	2	160
Patio	540	2	1,080
			6,820
MAINTENANCE			
Machine Shop	2,550	2	5,100
Meeting	240	1	240
Kitchen/Lounge	240	1	240
Restroom	80	2	160
Patio	540	2	720
			6,820
TOTAL			**50,616**
CIRCULATION			**X1.15**
			58,208

Parti:

1. The basic massing consists of the dome and support buildings.

2. A radial organization support multiple domes with minimal shadowing. Identical domes reduces costs and complexity.

3. Centralize support spaces creates a centralized hub which all circulation and activity will flow as well as reducing the distances between similar spaces.

4. Eliminating redundant spaces reduces the overall building footprint and cost.

5. Bring the canyon into the site, divide the mass into three masses with canyons between, assign each mass a function.

6. Shading over the canyon walls combats the desert heat, and keeps the building connected.

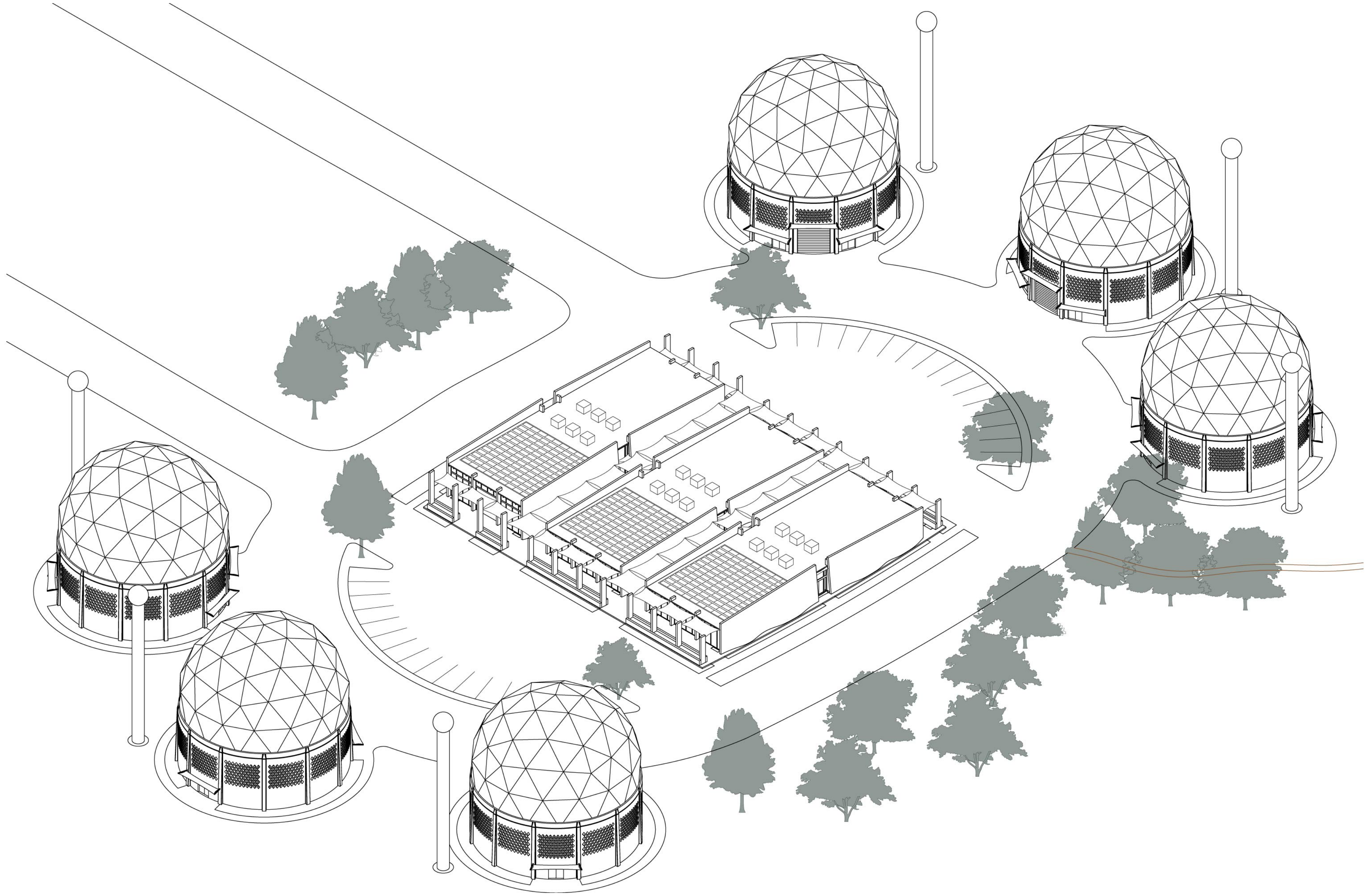
Program

The program is divided into four functions. The domes are identical, housing the telescope operation space. Each of the support spaces, office, control, and maintenance, begin with the same footprint and are filled with differing activities. The core of each support building consists of the same meeting room, kitchen/lounge, and a pair of restrooms.

Project Goals:

1. Explore 3D printing techniques as a method to reduce the labor component and thereby associated costs of the typical construction process.

2. Identifying additional design opportunities within the current printing technologies that could push that efficiency even further while also enhancing the aesthetics of the final product.



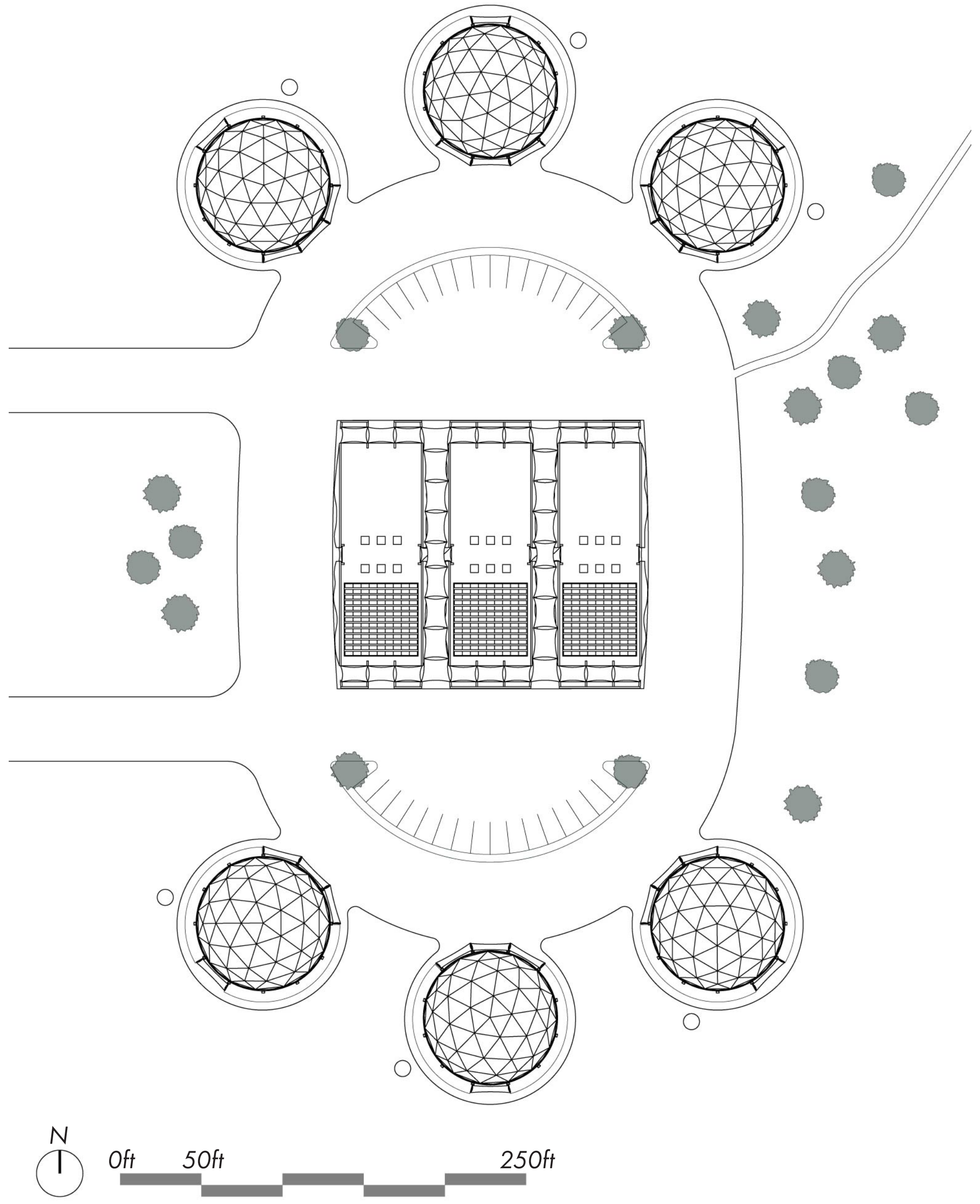
Site Isometric

Site Plan

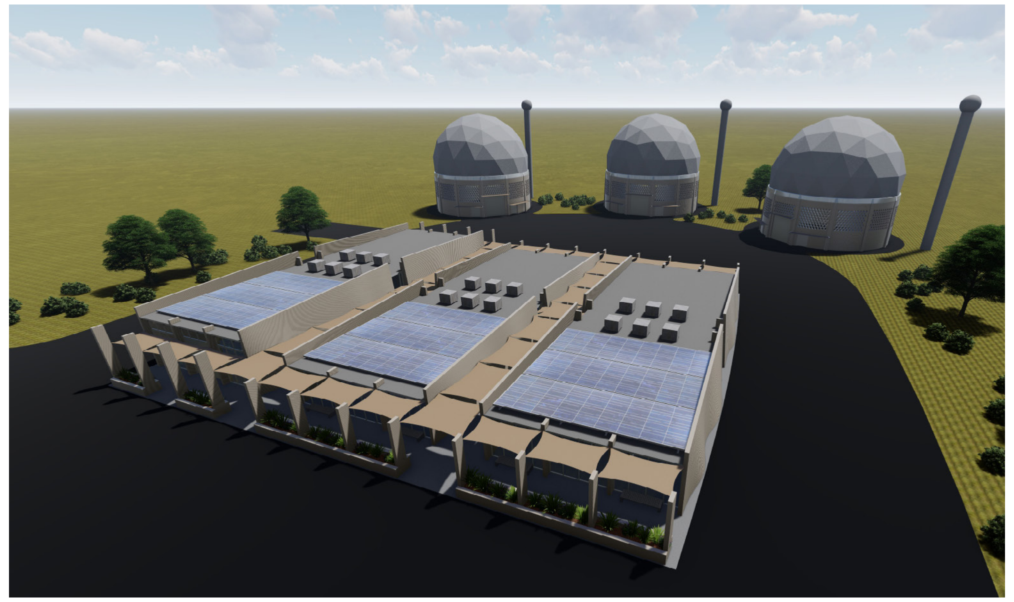
STRATA's site consists of six telescopes in a circular arrangement around a central control and support building. This layout allows for multiple telescopes working together as an interferometer while also minimizing how much they block, or shadow, each other's views.

Site access is from the east, at the intersection of *FM-285 and TX-207. This intersection would continue either directly to the observatory, or through a larger campus of support spaces and other telescopes.*

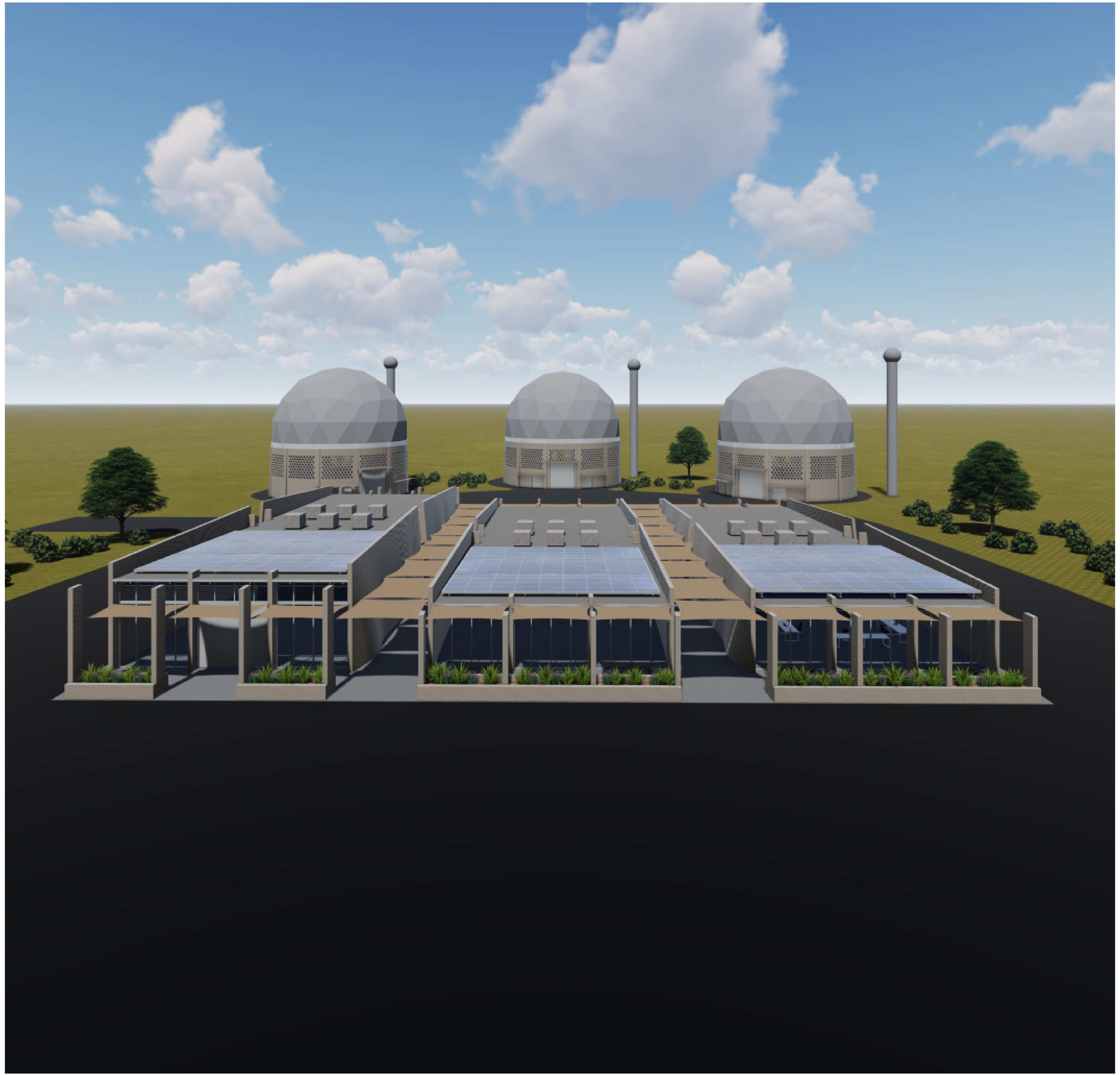
Parking on the north and south sides of the building allow for easy access to both the telescopes as well as entry into the building's 'canyons'.



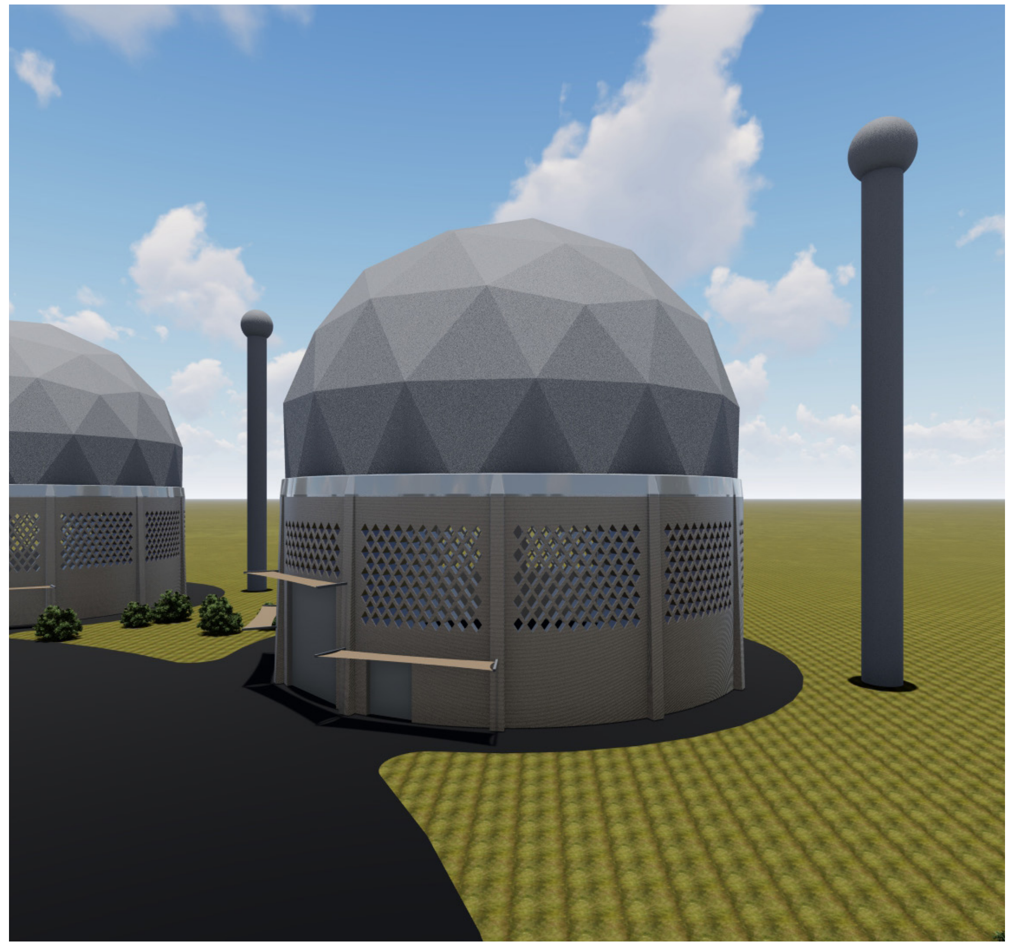
Site Plan



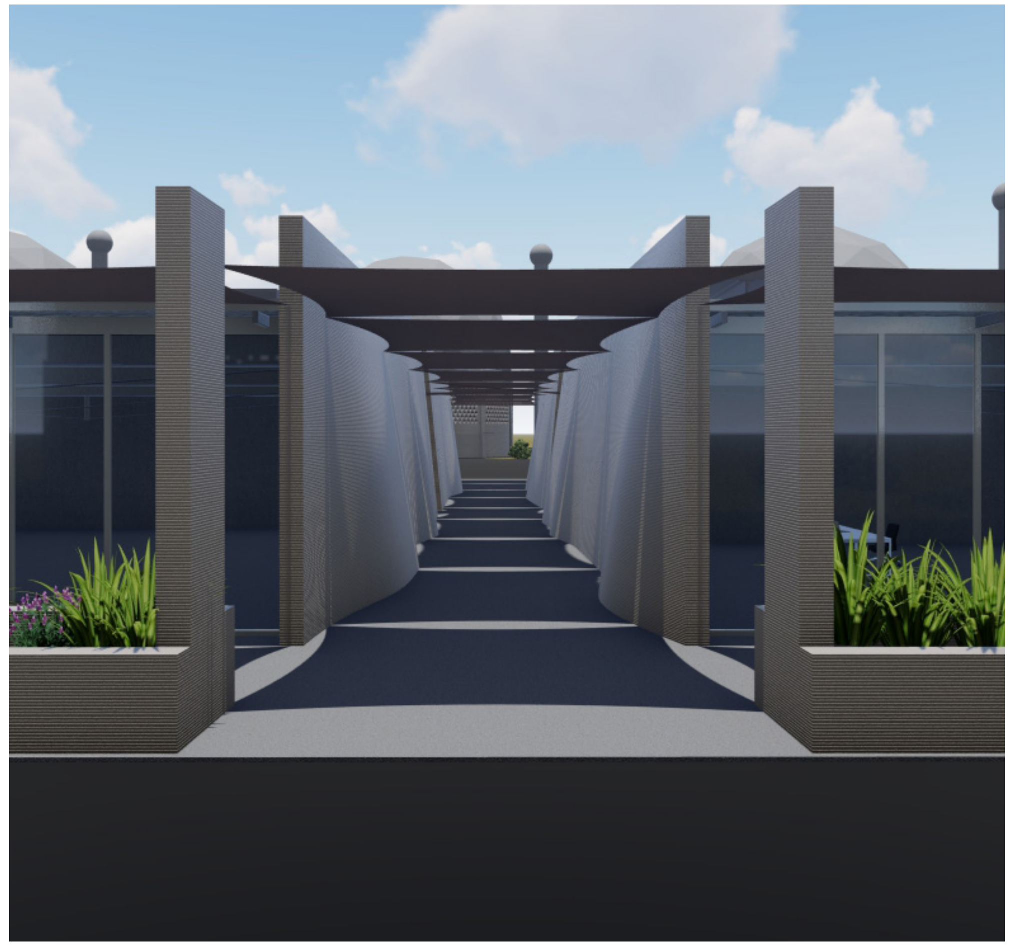
Render, Site



Render, Wide



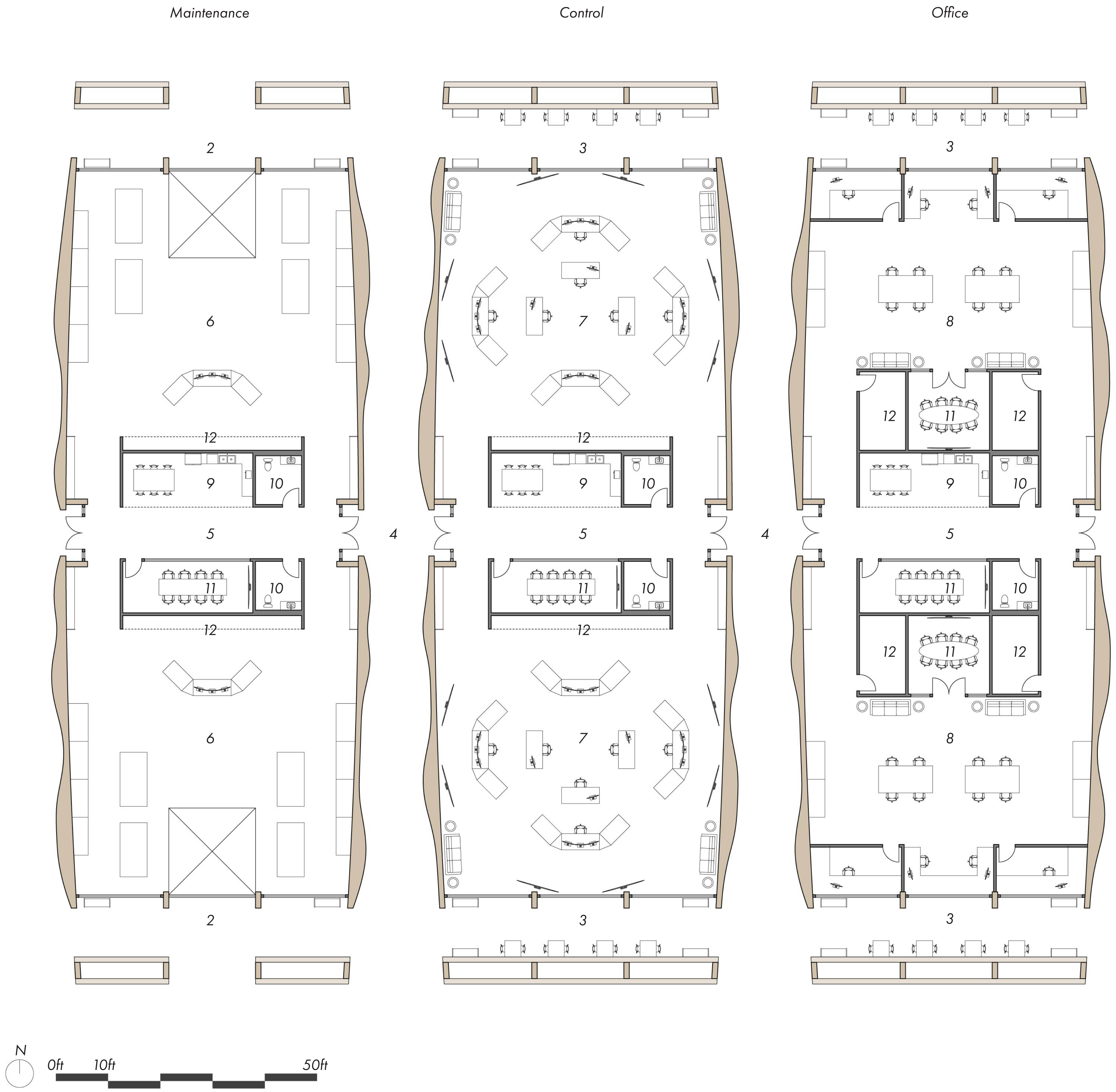
Render, Observatory



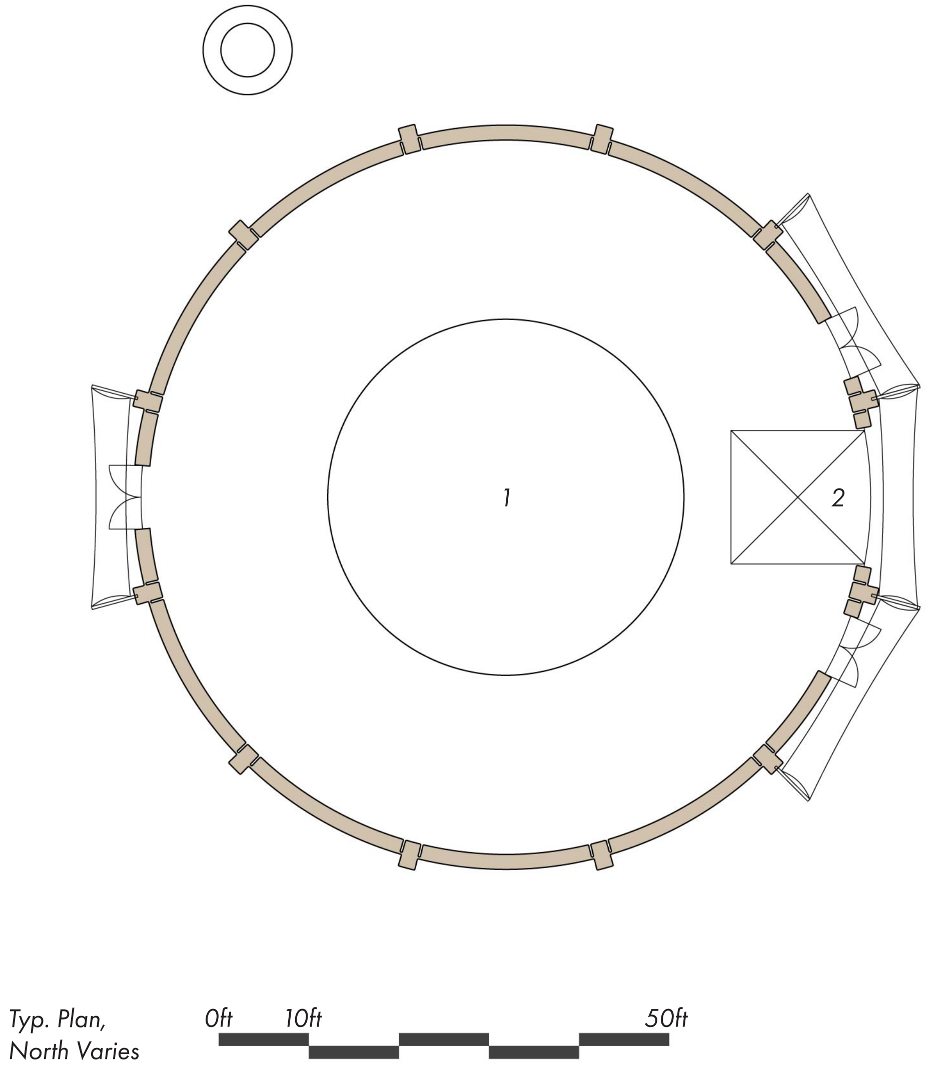
Render, Canyon

Renders

The STRATA Observatory pushes the boundaries of what is capable with 3D printed construction and astronomical interferometry. There are construction limitations that keep STRATA from being built now, but several innovative techniques integrated into the project help to imagine the direction both fields might move in the near future.



Observatory Support Spaces Floor Plan



Observatory Dome Floor Plan

Room key
1. Telescope
2. Loading
3. Patio
4. Canyon
5. Hall
6. Machine Shop
7. Control Room
8. Office Space
9. Kitchen/Lounge
10. Restroom
11. Meeting Room
12. Storage

Floor Plans

The observatory domes are fairly simple in plan. Each is an 80ft diameter circle, large enough to allow the telescope within to spin fully without any hindrances.

Access into the domes is via three sets of double-doors, two in the front facing the support buildings, and one in the back for emergency and utility egress. Additionally, a large garage door in the front facilitates access for large vehicles as parts are moved in or out of the domes.

The support spaces are divided into three distinct buildings, separated by sloped waving walls that imitate the sandstone layers of the nearby canyon. These canyon spaces are the primary access to the buildings, but they also serve as buffer spaces to prevent crowding and to shorten access to the outdoors.

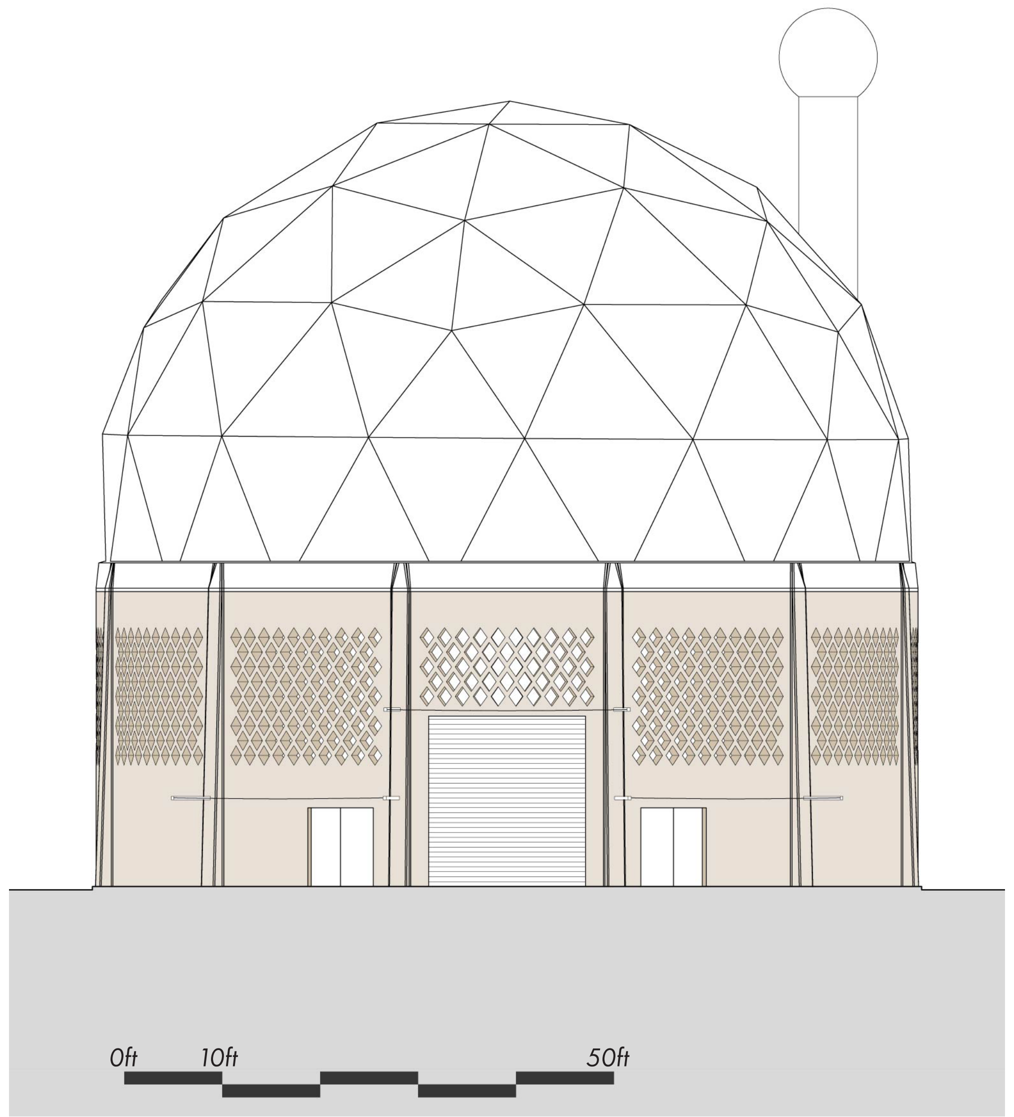
A central hallway flows in and out of each support space to create a long path from building to canyon to building. The three distinct buildings are, from east to west:

Office: in which ancillary support spaces such as administration, technology services, and large meeting rooms are located

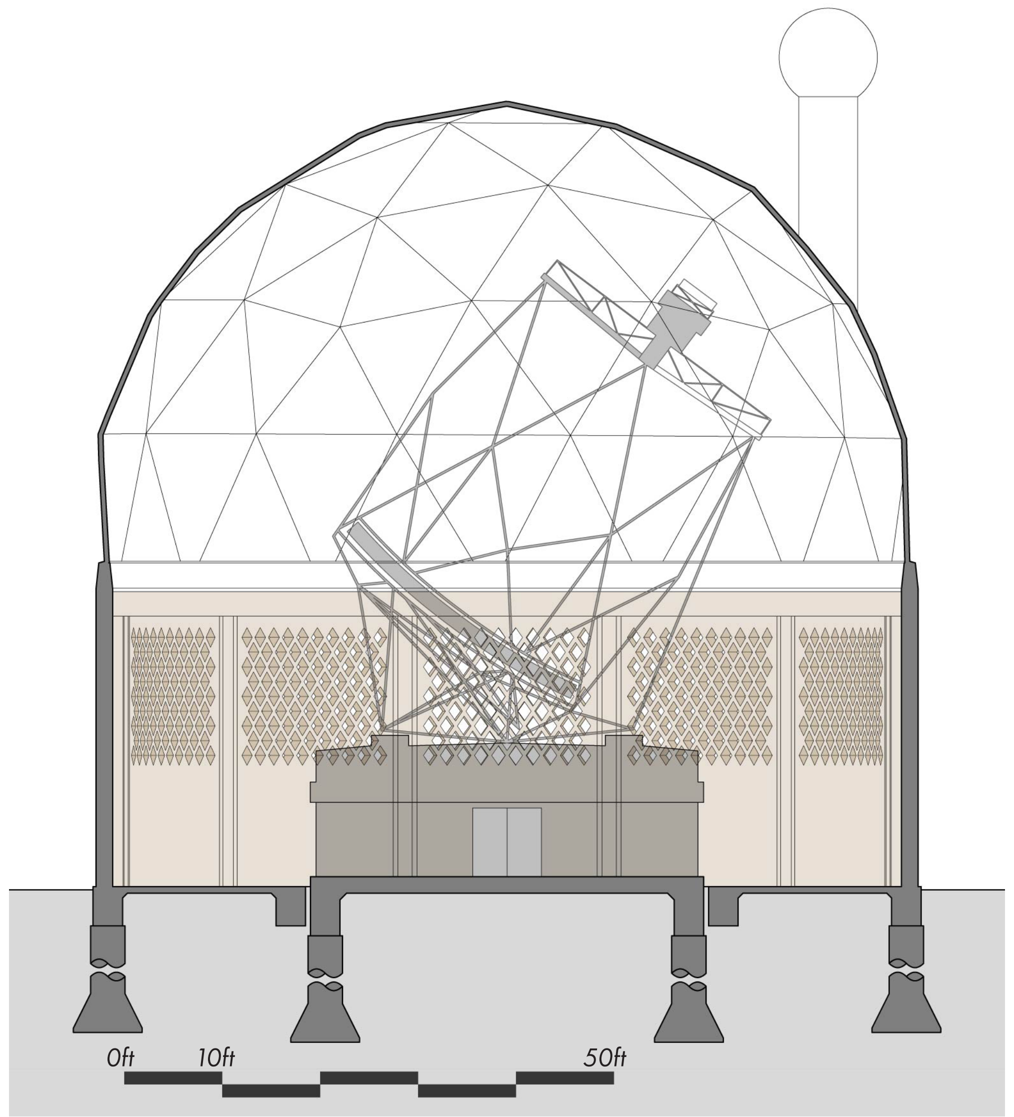
Control: consisting of two large control rooms, each with enough space for three sets of desks from which operators can monitor and move the telescopes.

Maintenance: made up of two large workshops where telescope parts can be cleaned, repaired, or fabricated.

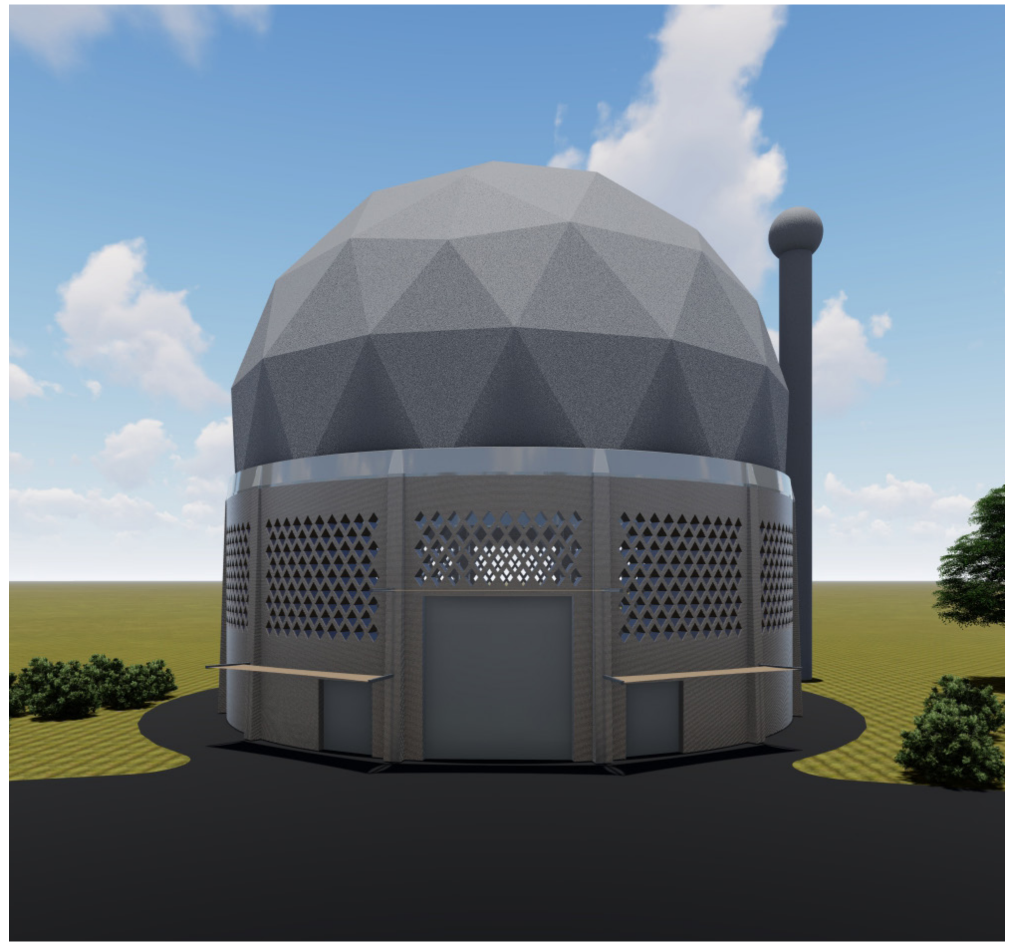
In each building, the central hallway is flanked by a kitchen/lounge, meeting room, and restrooms. Beyond these consistent spaces, a short hallway opens into a larger room where the building's unique functions occur. At the far end of this space are curtain walls, allowing full views of the telescopes and sky. Just outside these curtain walls are patio spaces with seating and secondary circulation. These patio spaces and the canyons are shaded with cloth canopies to protect from sun and rain.



Observatory Dome, Front Elevation



Observatory Dome, Section



Render, Observatory Domes

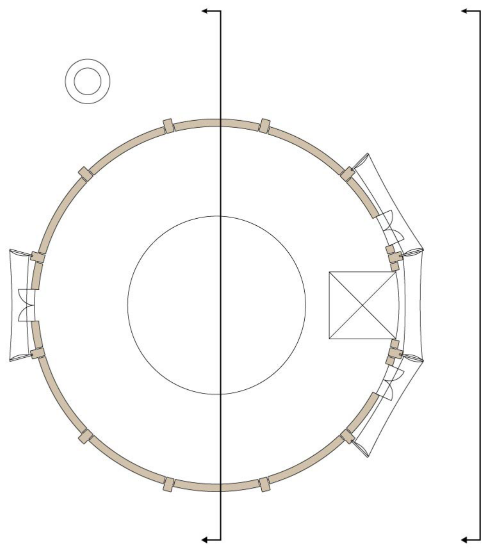
Dome Elevation

STRATA observatory has six unit telescopes, housed in independent domes. The domes are 3D printed concrete cylinders, capped light-weight, metal, geodesic spheres. Each dome is 80ft in diameter at ground level, 86ft at the widest part of the geodesic sphere. They are approximately 73ft tall, ground to tip, with the 3D printed wall reaching 30ft high.

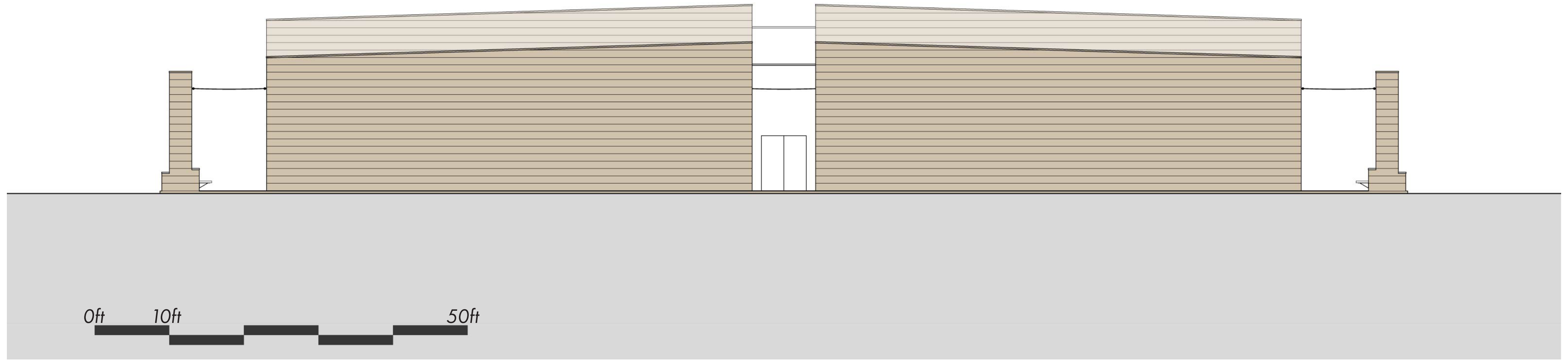
Each dome contains and protects a telescope within. The temperature, lighting, and humidity are all monitored around the clock. While the spaces are not conditioned, the insulation and ventilation allows for precise control of the climate inside.

The domes are joined by a tall, slender tower. These columns are alignment towers. Each sphere is a known point, that the adjacent telescope can focus of calibrate too before it turns to view the night sky.

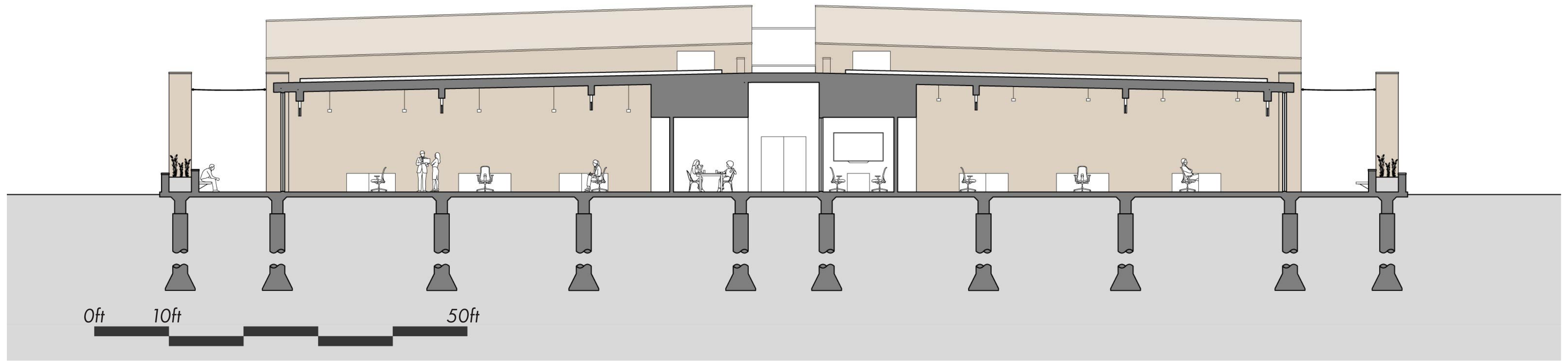
The identical nature of each dome allows for reduced costs, both at time of construction, and during maintenance over the course of the observatory's life span. Similar parts, allow for reduced complexity and consistent maintenance.



Cut Planes



Observatory Support Space, East Elevation



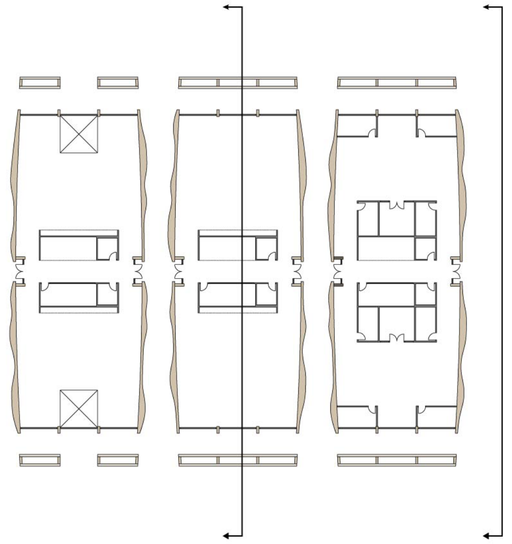
Observatory Support Space, Transverse Section

Render, Porches

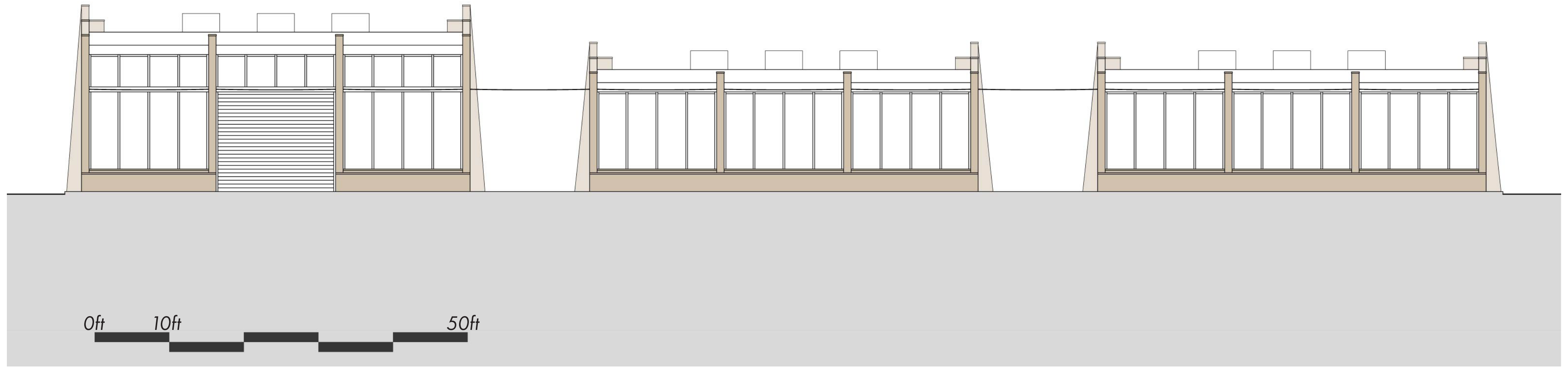
East Elevation

From the east elevation, the semi-flat face of the support building fills the view. This wall would absorb heat during the day, particularly in the morning while the west wall sees the afternoon sun.

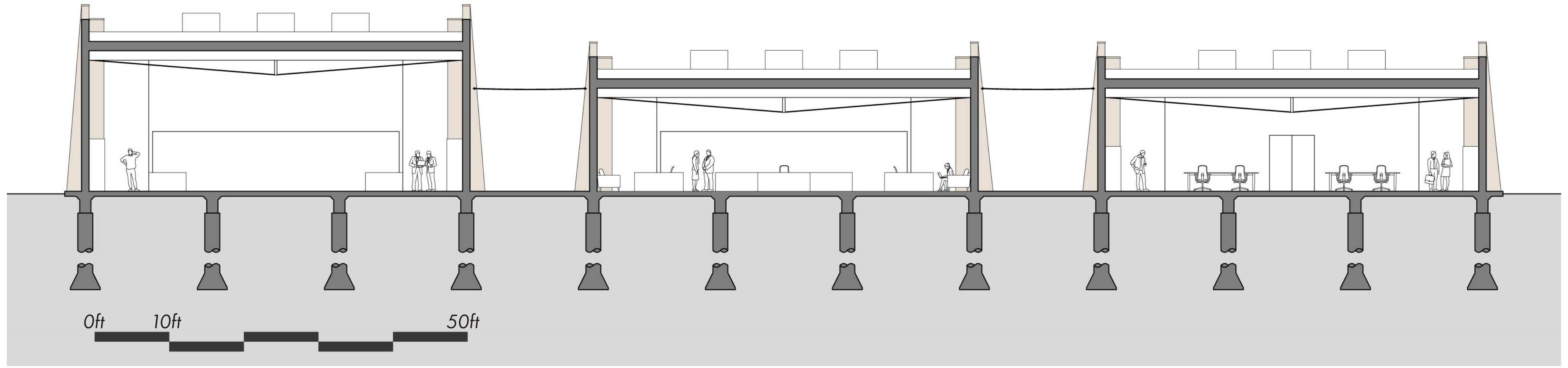
Inside, the control rooms are shown, facing outwards towards the telescope domes in the distance. These control rooms flank the central hall way and lounge/meeting spaces at the core of the building.



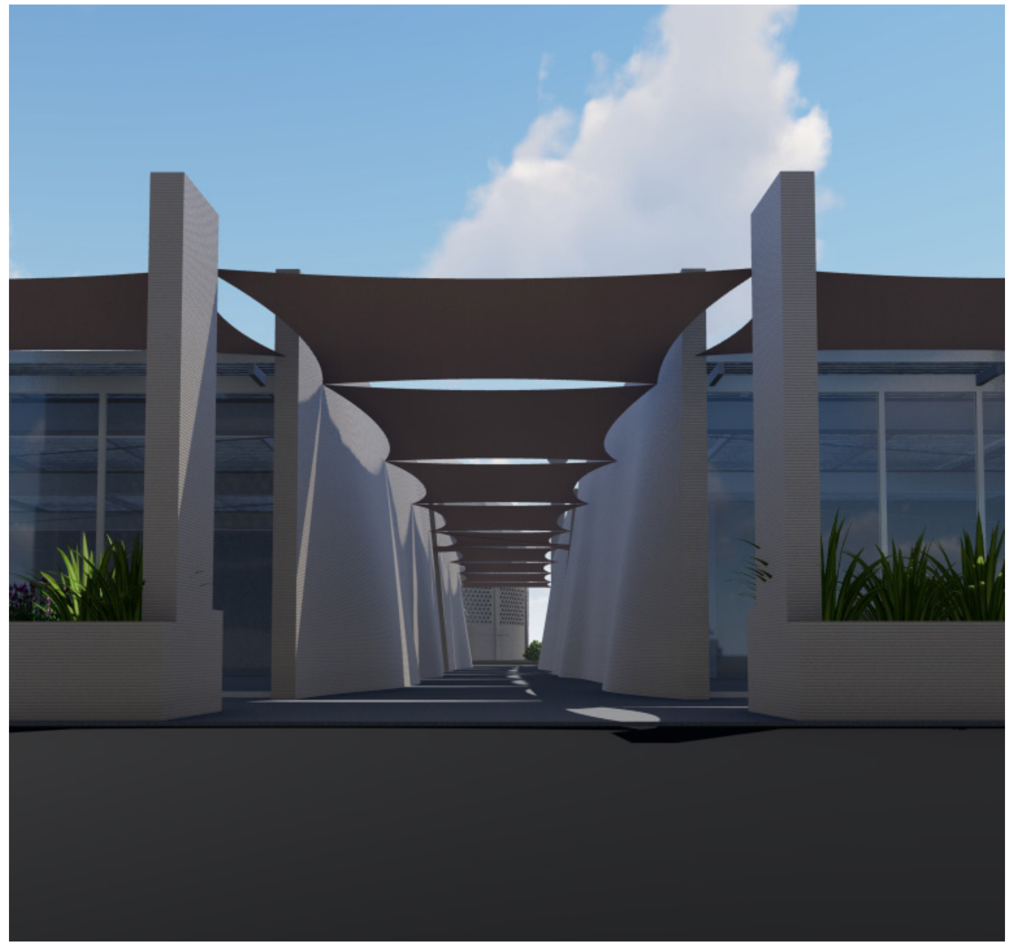
Cut Planes



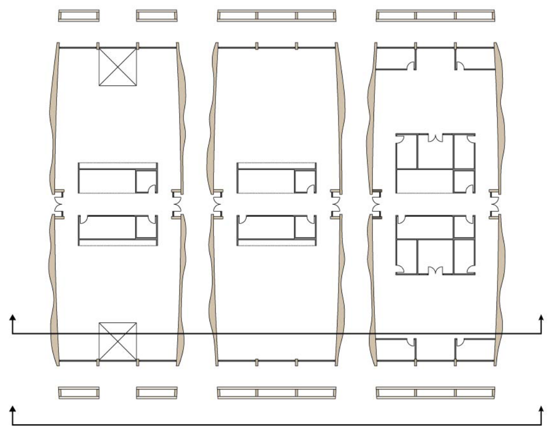
Observatory Support Space, South Elevation



Observatory Support Space, Longitudinal Section



Render, View Into 'Canyon'



Cut Planes

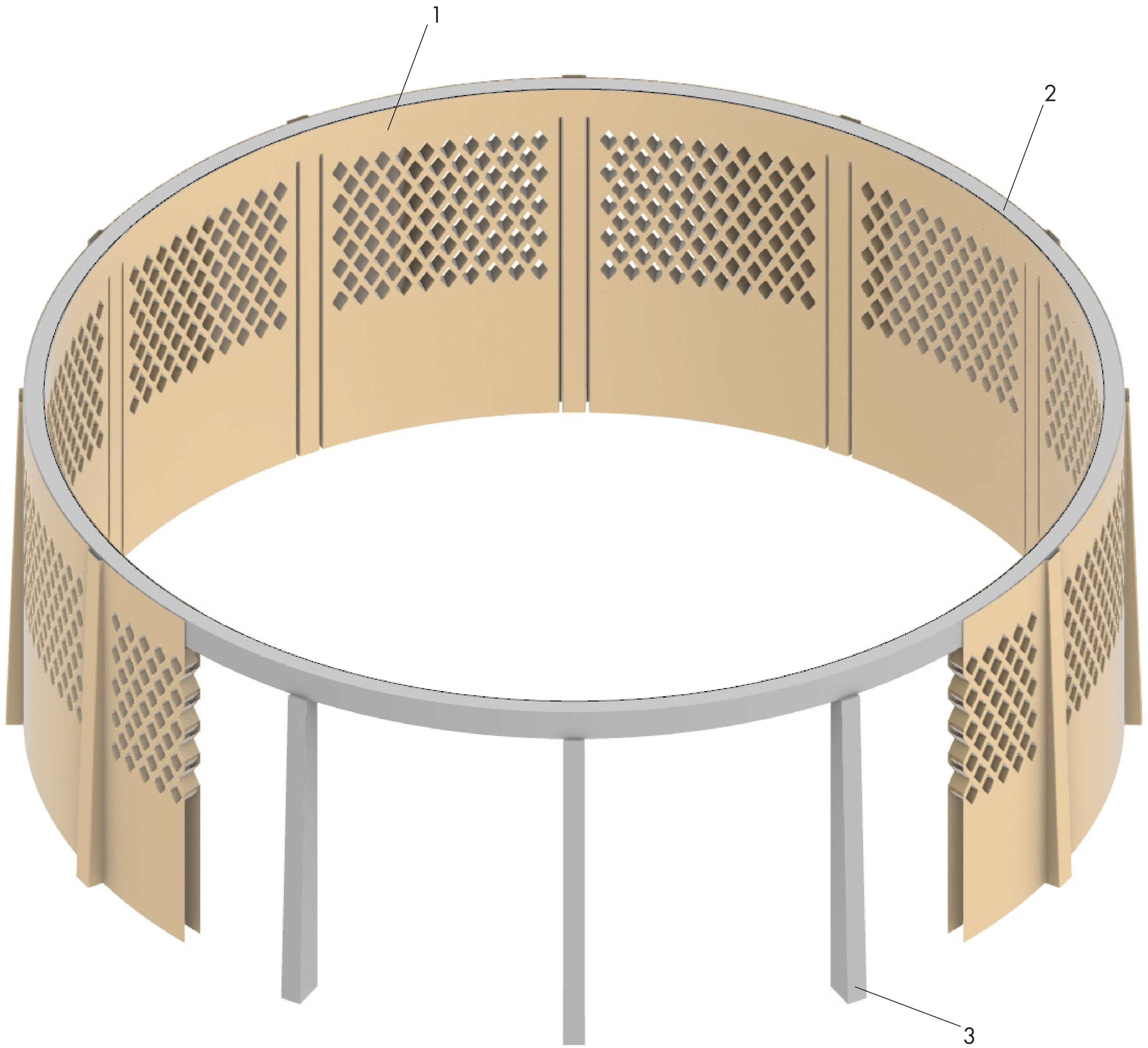
South Elevation

The south elevation and section show a clear image of the individual support buildings in parallel. The curtain walls are visible in the elevation, along with the 3D printed columns that support the cloth roof over the patios. The section shows the three function spaces with the canyons between. Further, the section shows the higher roof of the maintenance space and the inverted king trusses that support the roof.

4

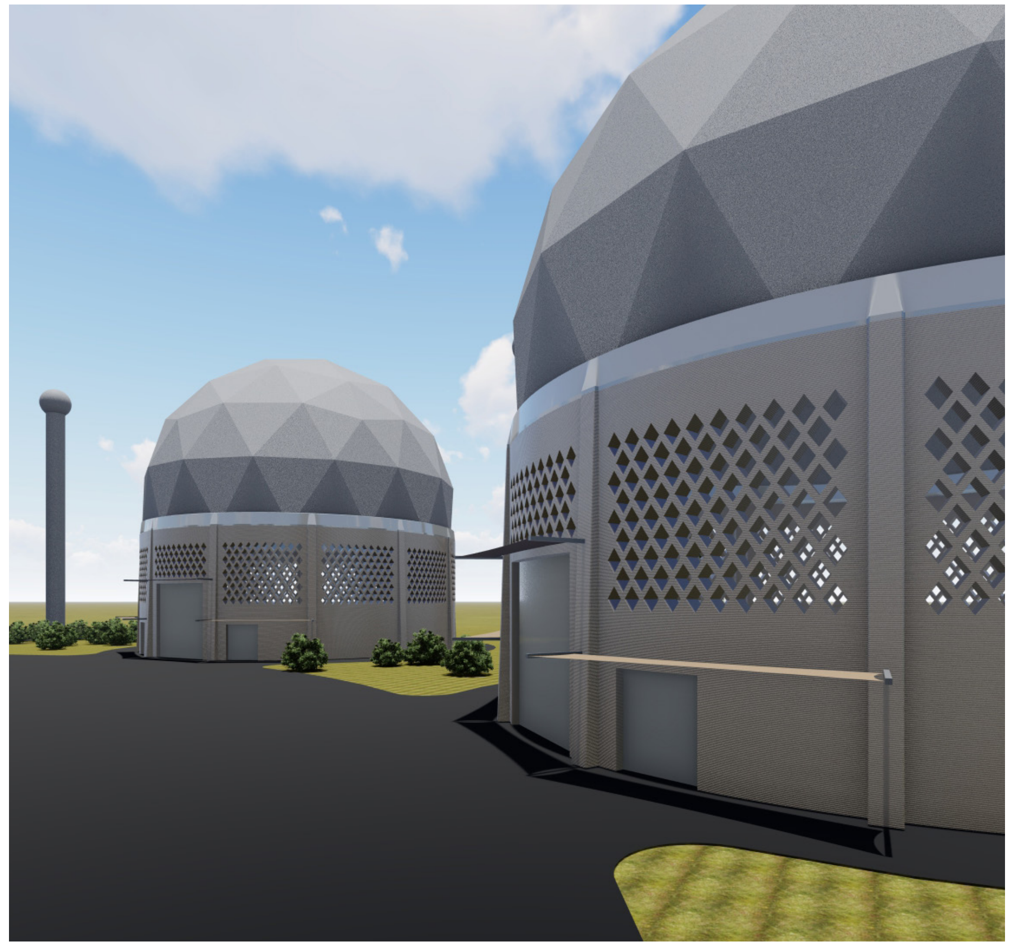
INTEGRATION

The following chapter demonstrates the methods and ideas utilized to embed and integrate structural and environmental systems into the body of the 3D printed walls.

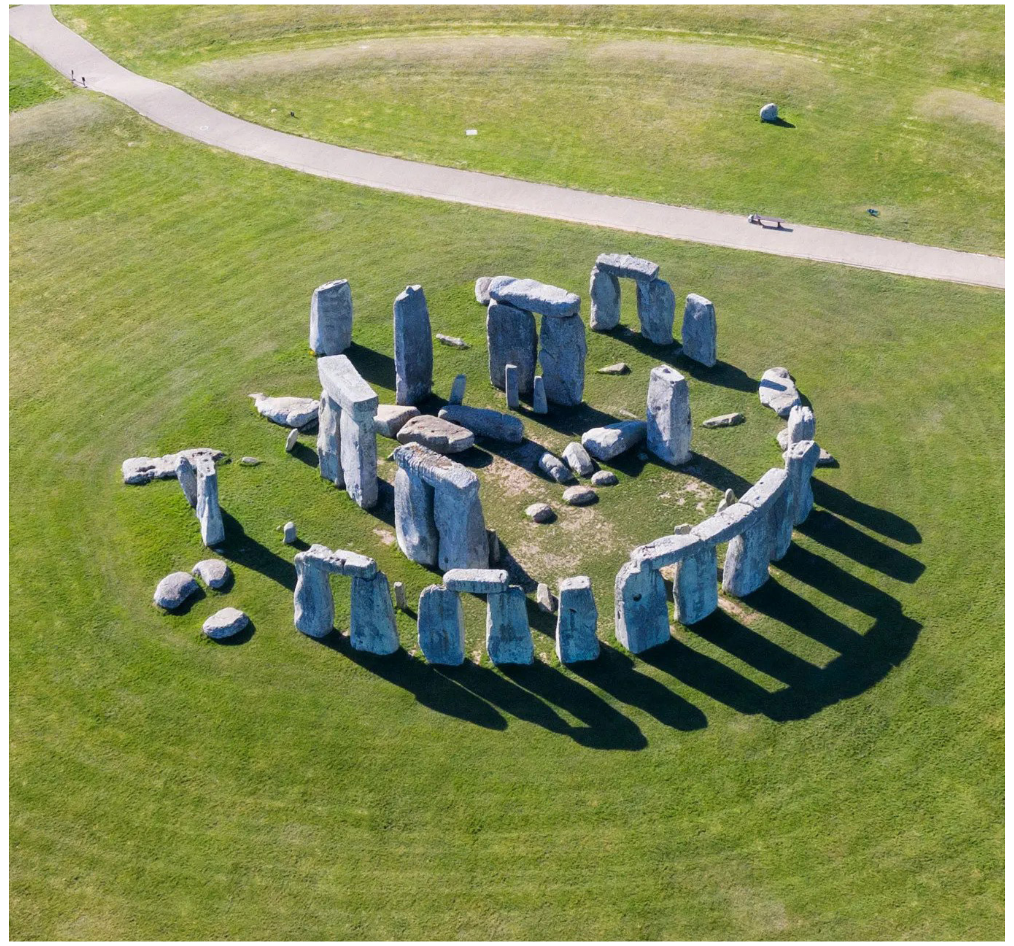


1: 3D Printed Concrete Wall
2: Cast-in-place Concrete Perimeter, Beam Inside Wall
3: Cast-in-place Concrete Column(s), Inside Wall

Observatory Dome Structural Bones Model



Render, Dome Exterior

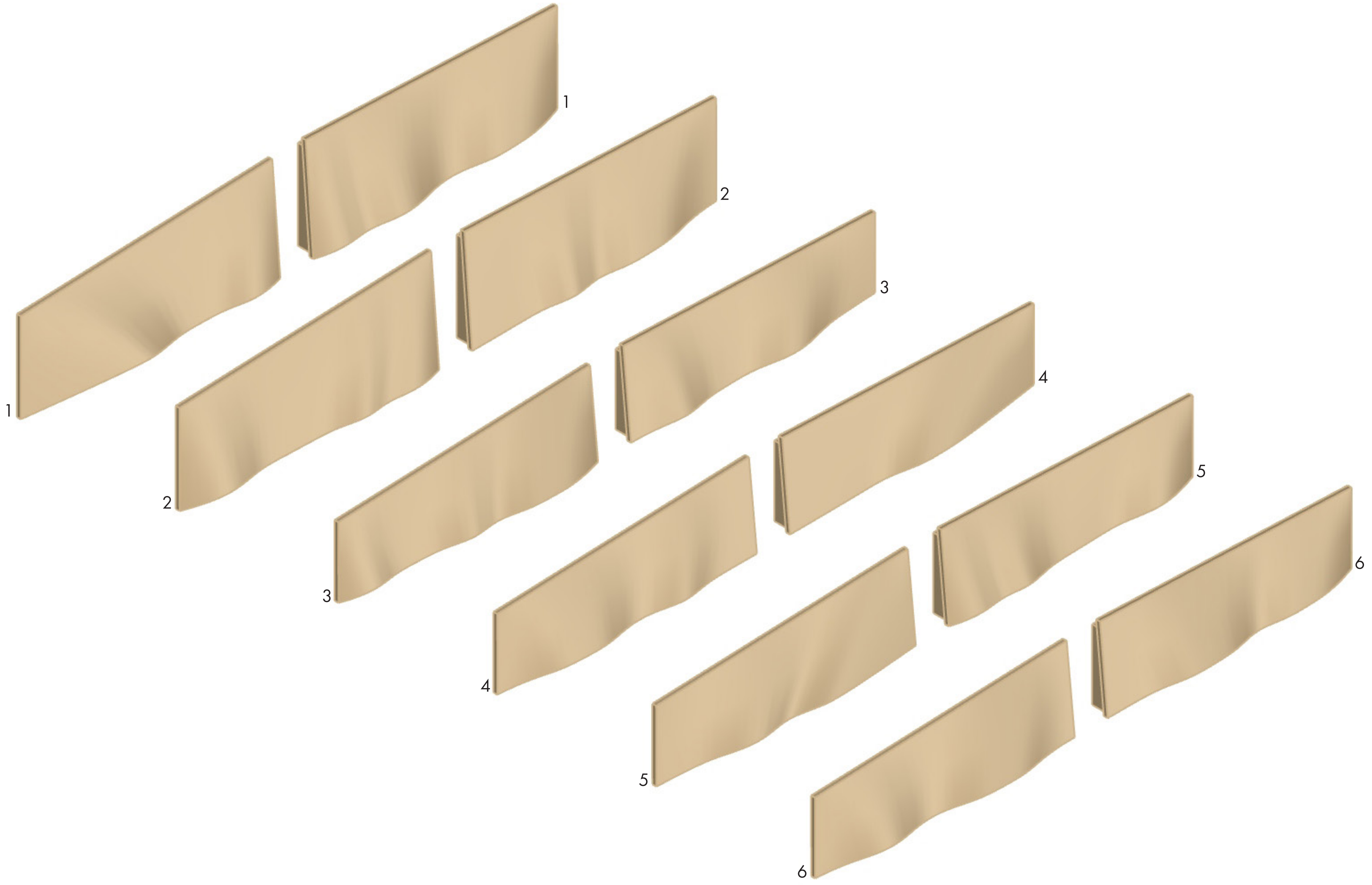


Stone Henge, England *Figure 51*

Dome Structure

The dome walls are designed at 30ft tall open, unbraced space. Current 3D printing methods cannot construct such large unsupported spans out of the light-weight concrete or clay mixes. To active the lofty heights, reinforced cast-in-place concrete columns and a perimeter beam are to be installed, building on the ideas at Dubai Municipality Building.

Each column is approximately 3ft by 2ft at the base, an tapers narrower towards the top. On top of these columns, a perimeter beam, 1.5ft thick by 2.5ft tall, wraps around the building, tying the columns together and supporting the steel dome above.

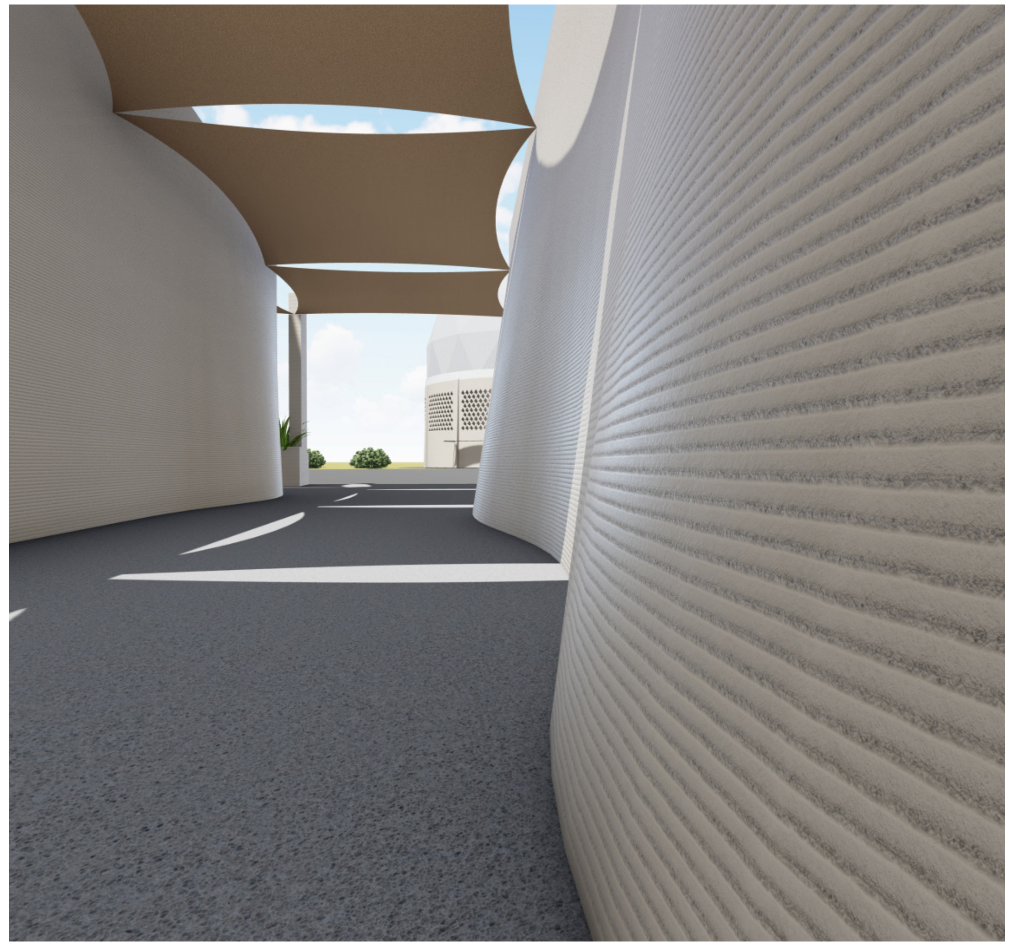


3D Printed Support 'Canyon' Wall Patterns

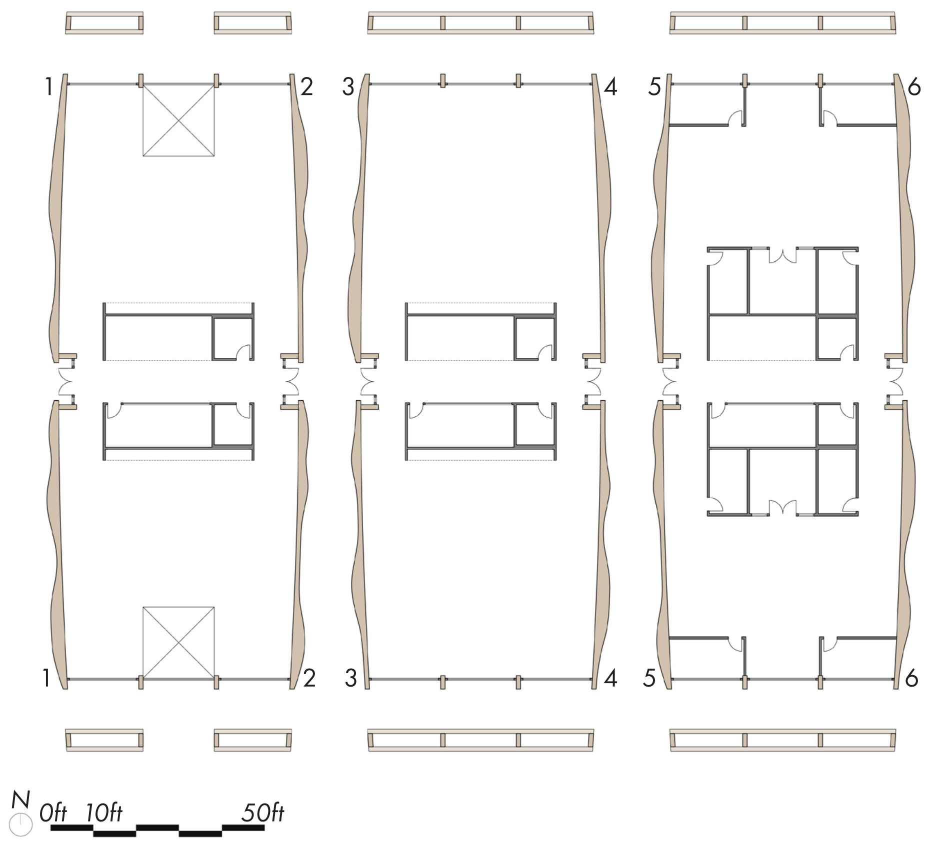
Walls

Each of the support buildings' twelve 3D printed walls mimic the texture and forms found in nearby Palo Duro Canyon. By mixing in local clays, the color and texture of the wall connect to the environment on which the site is located.

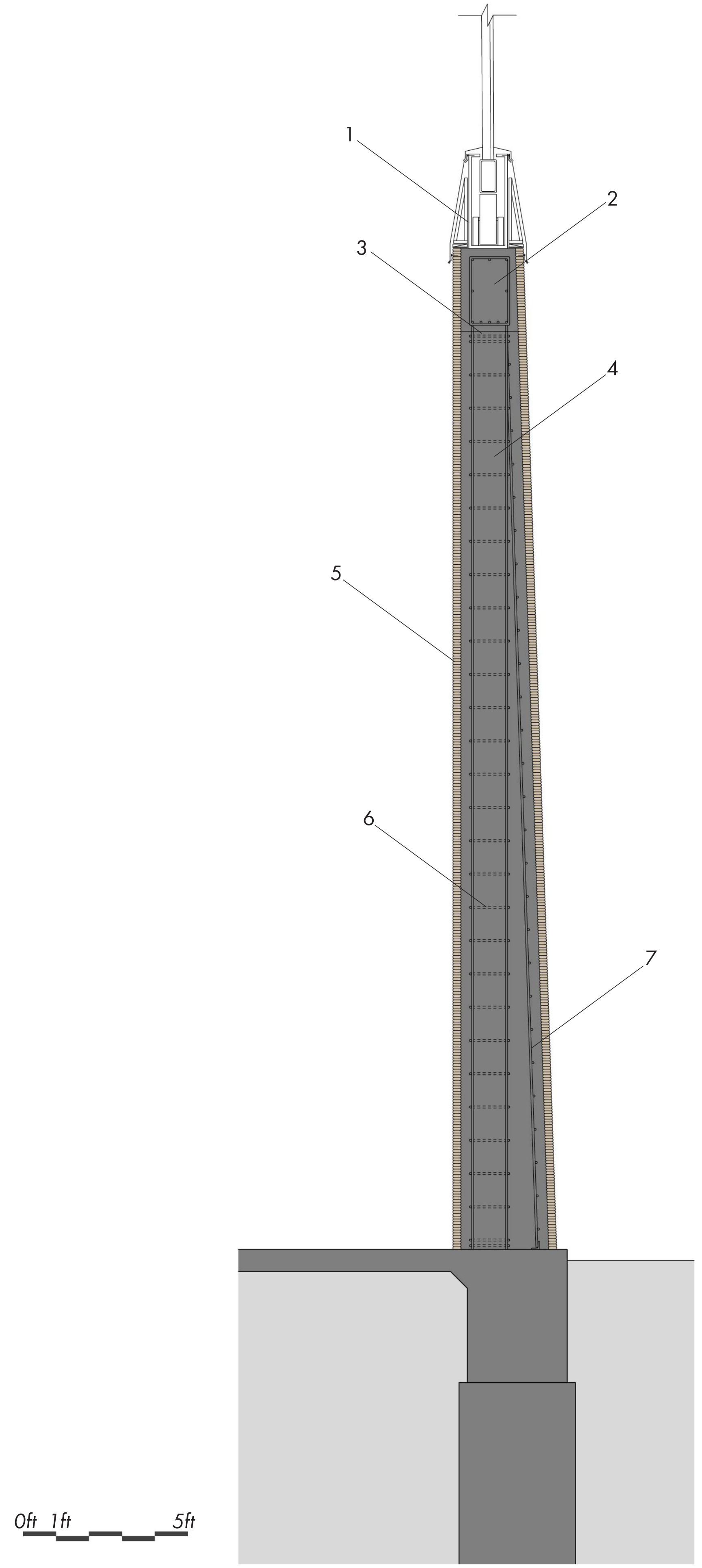
Some of the canyon walls presented here have been rotated so the waving faces are all visible.



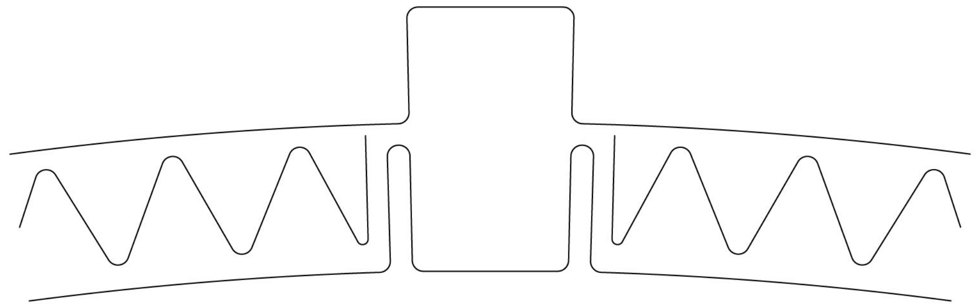
Render, Canyon Walls



Support Wall Key

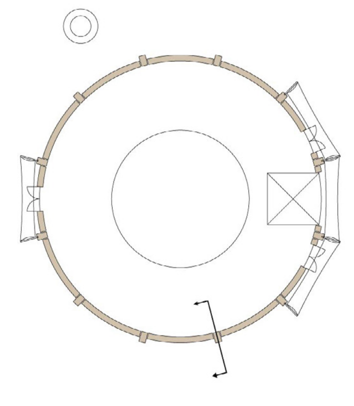


Dome Wall Section



Dome Wall Print Pattern

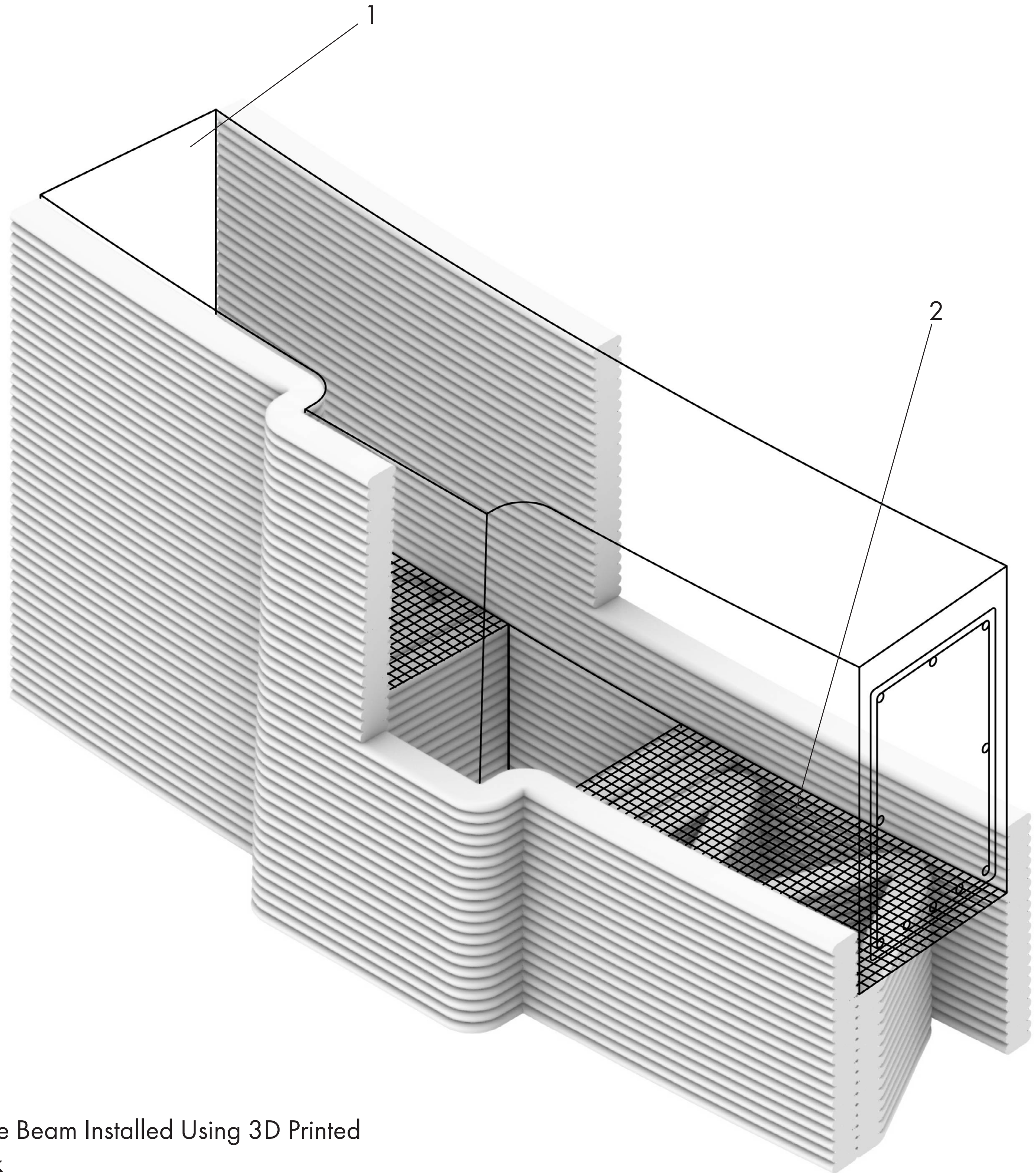
Key:
1: Observatory Dome Roller Machinery
2: Reinforced Concrete Beam Installed Using 3D Printed Concrete as Formwork
3: Thin Wire Mesh to Retain Concrete
4: Reinforced Concrete Column Installed Using 3D Printed Concrete as Formwork
5: 3D Printed Concrete Wall, Thickness Varies
6: Rebar Cage
7: Additional Rebar to Prevent Spalling



Dome Wall Section

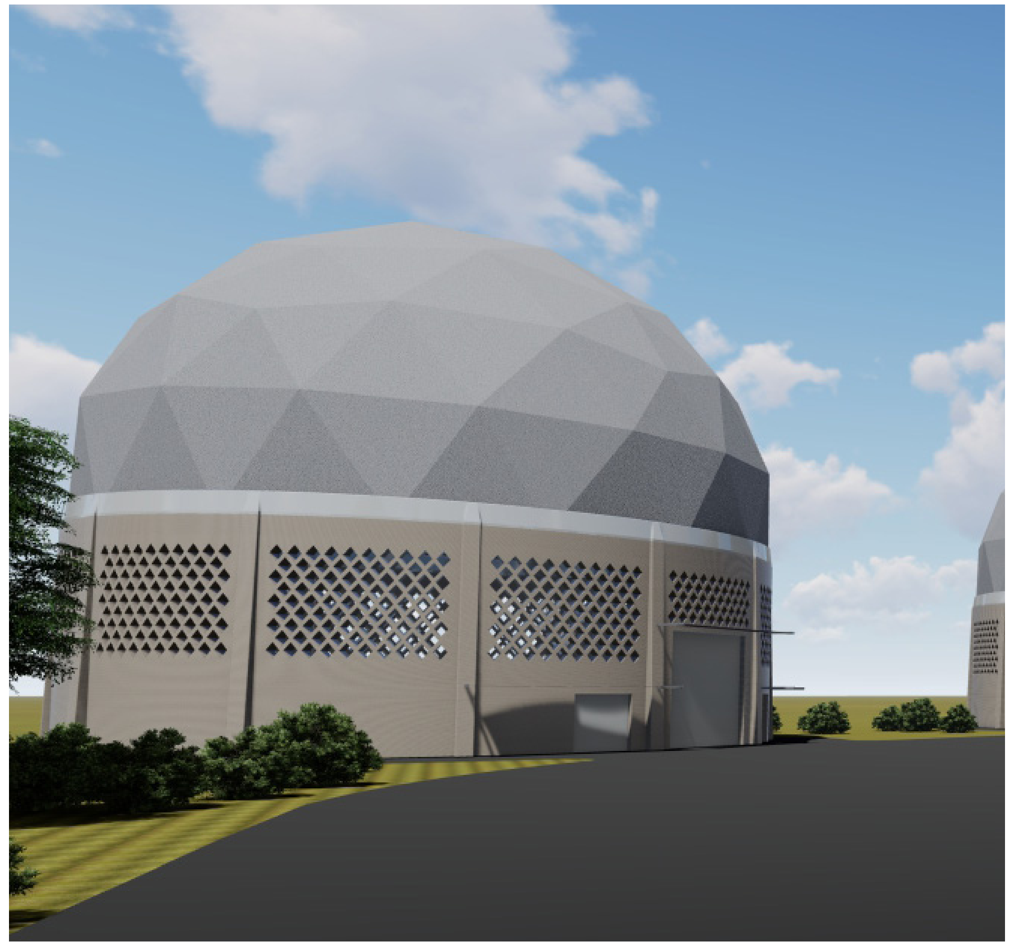
The walls of the dome are 30ft tall, reinforced to stand under the weight of the dome and the long unbraced height. These walls are printed of the same concrete-clay mixture as the support buildings. The tapored columns and the 3D printing layering inspires parallels with the hoodoos of Palo Duro such as the Lighthouse.

Dome Isometric Section



1: Reinforced Concrete Beam Installed Using 3D Printed Concrete as Formwork
2: Thin Wire Mesh to Retain Concrete

Concrete Perimeter Beam

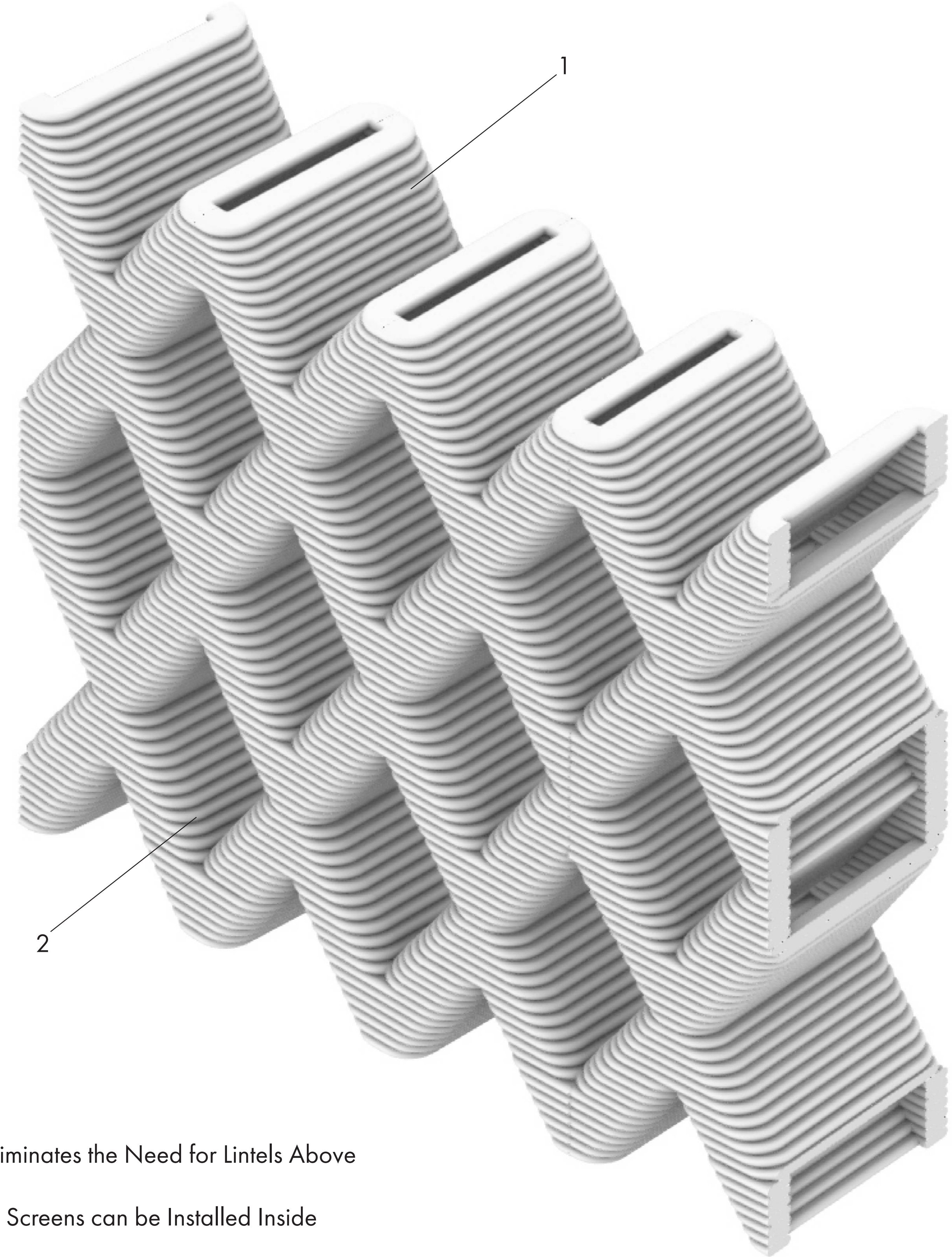


Render, inside dome looking out

Location Key

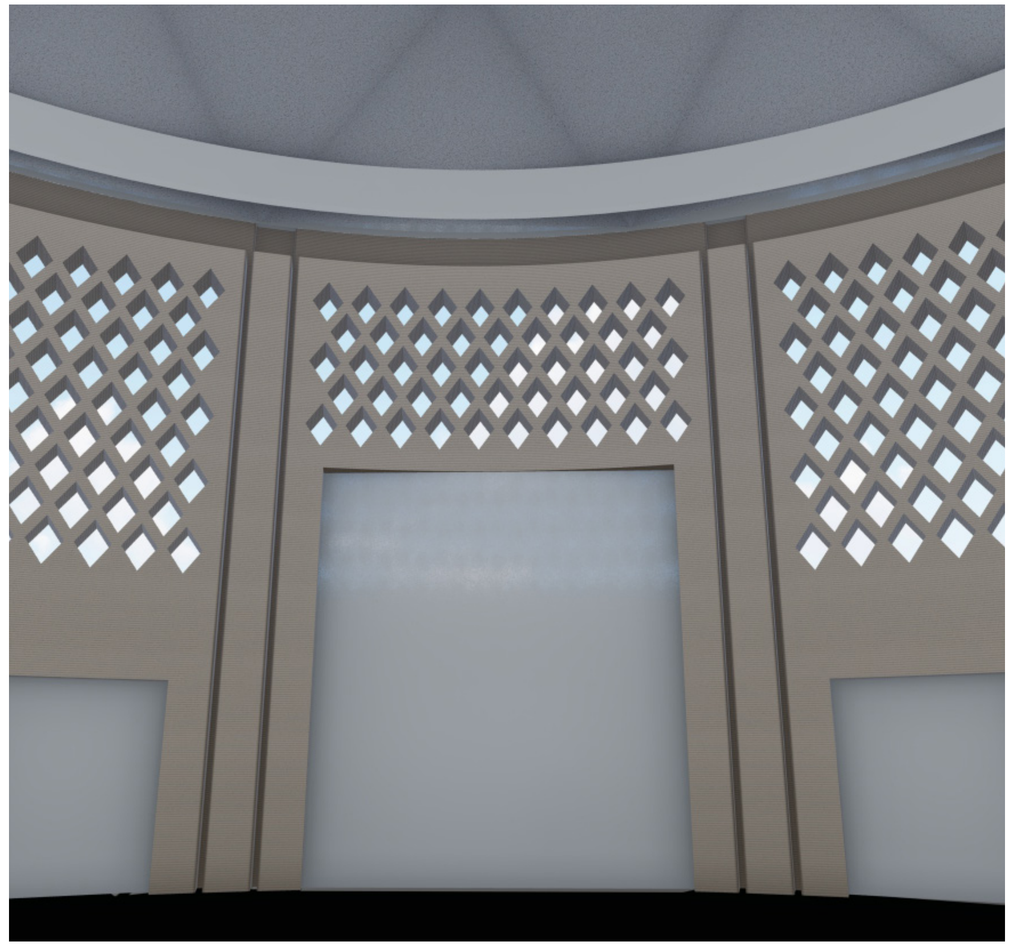
Structure Integration

The perimeter around the top of the domes' walls is reinforced with a deep cast-in-place concrete beam within the wall. The beam, 1.5ft thick by 2.5ft tall, is poured into a continuous void, contained by 3D printed formwork. This beam serves the double purpose of tying the columns together and supporting the steel dome above.

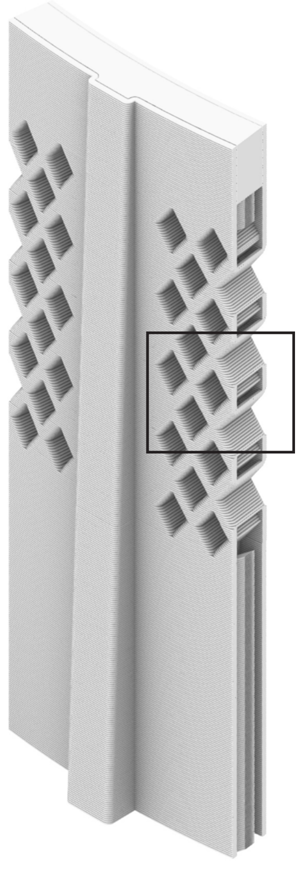


1: Diamond Shape Eliminates the Need for Lintels Above Each Opening
2: Mesh or Operable Screens can be Installed Inside Each Opening

Ventilation Openings



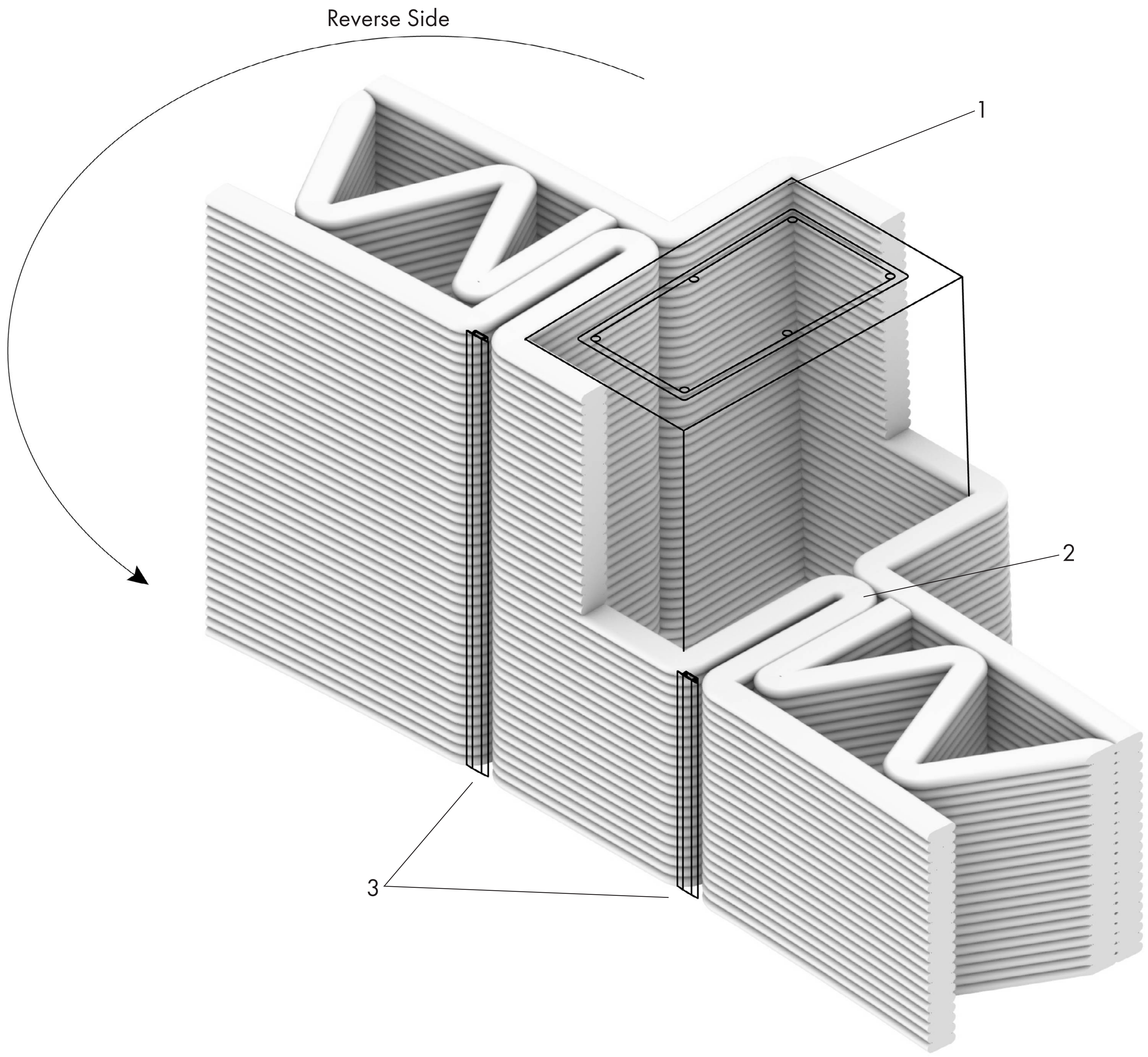
Render, Dome Ventilation



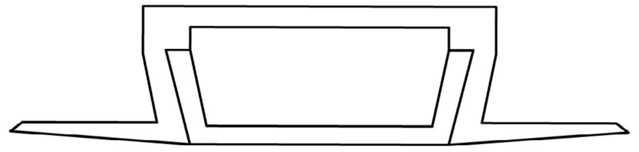
Location Key

Ventilation Integration

The air within the dome needs to be controlled and vented to protect the telescope from the heat of the day, and to maintain a constant air temperature with the outside air during operation at night. To achieve this, ventilation openings are printed into the dome walls. The diamond shape of the vents allows for open airflow without complitating the printing process with the need for lintels above each opening.



1: Reinforced Concrete Column Installed Using 3D Printed Concrete as Formwork
2: Printing Pattern Reinforces Column Edge
3: LED Light Strips Installed in Groove After Construction



LED Light Strip
Section

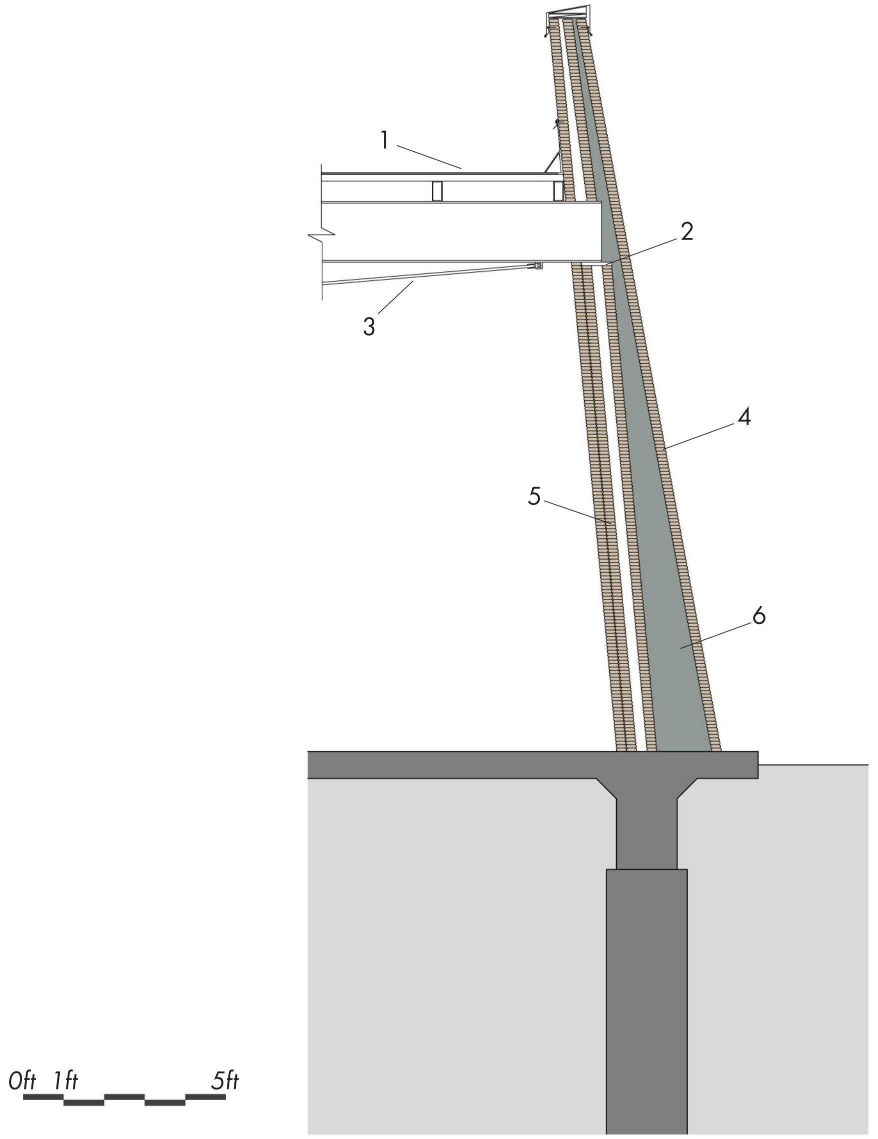
Column and Lighting

Columns and Lighting

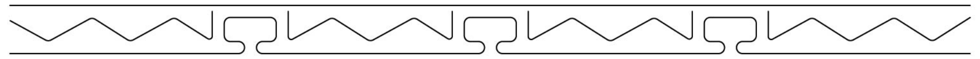
To facilitate the concrete column with the dome wall, the print pattern is altered to reinforce the column sides with a double layer. This has the effect of creating a vertical groove in the wall, visible from the inside. Taking advantage of this, LED lighting strips run the fill height of these grooves, creating an embedded lighting solution that can be easily adjusted.

LED Light Strip Casting *Figure 52*

Location Key

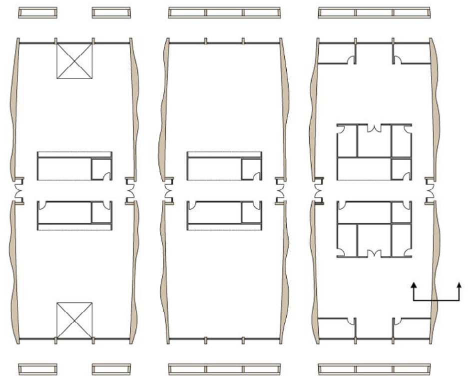


Support Space Wall Section



Support Wall Print Pattern

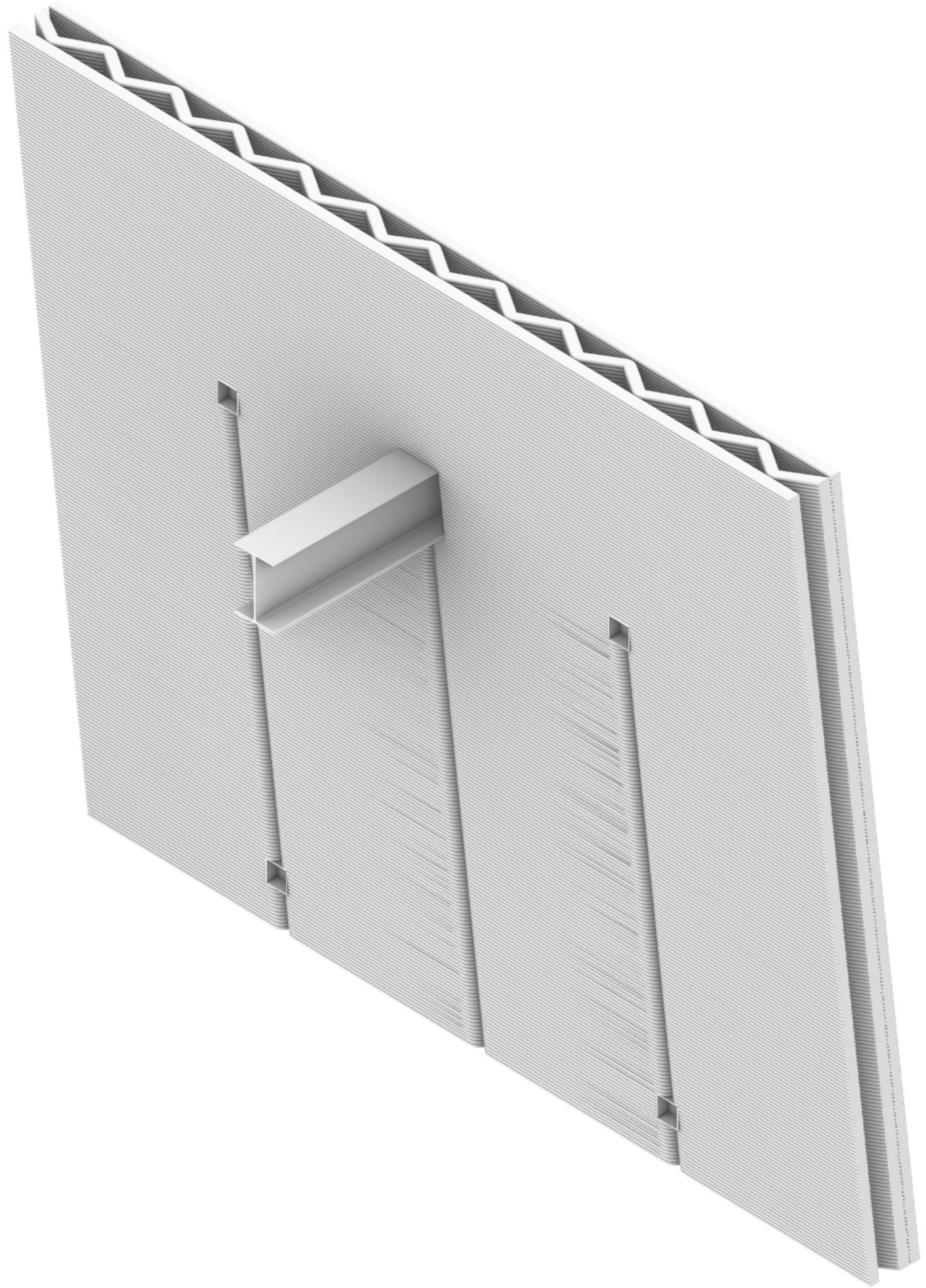
Key:
1: Corrugated Metal Roof
2: Sill Plate Under Beam, Embedded in Wall During Printing
3: Inverted King Truss @12ft Above Finished Floor
4: 3D Printed Concrete Wall, Thickness Varies
5: Reinforced Print Pattern Under Beam
6: Spray Foam Insulation



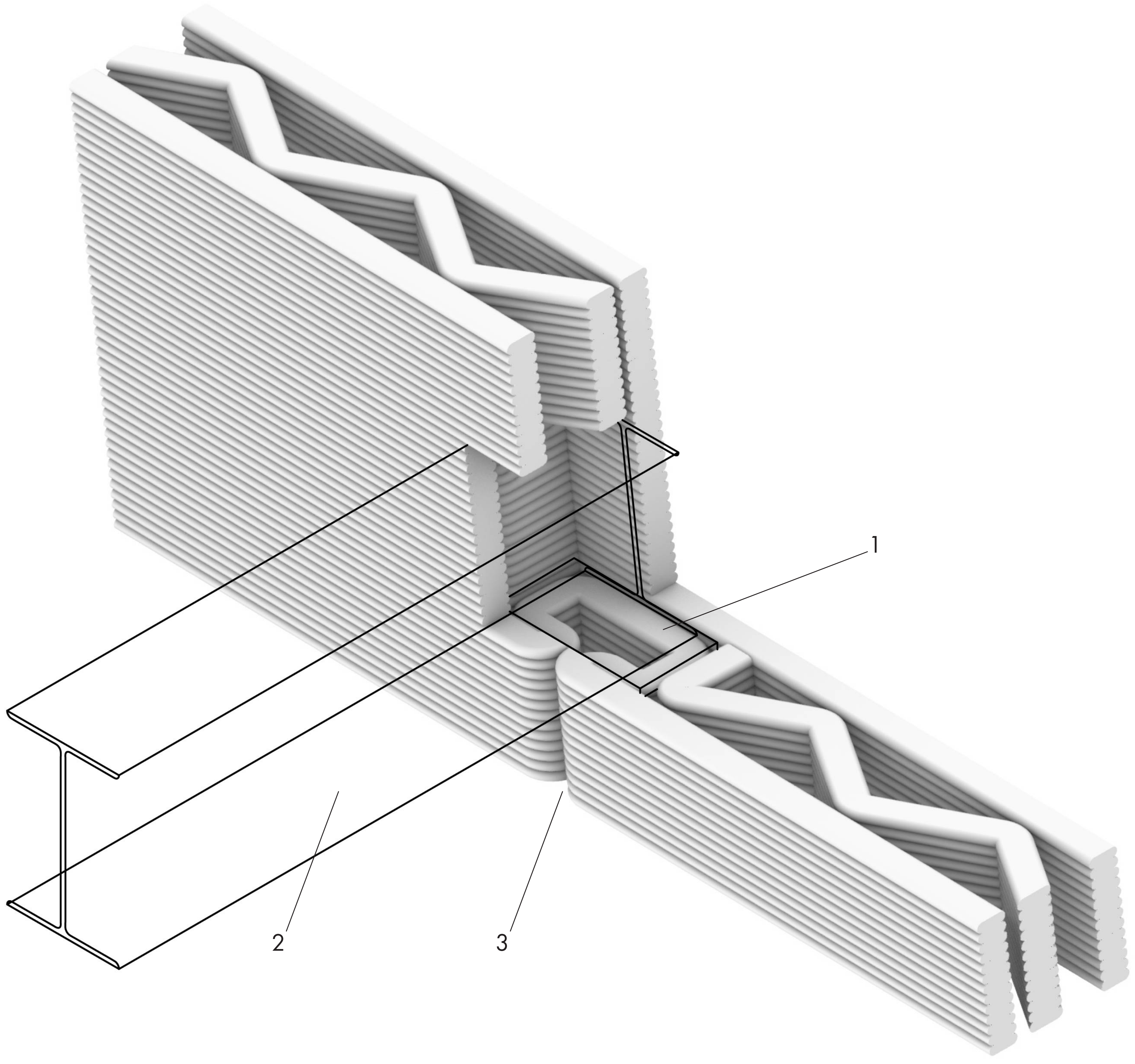
Render, Canyon

Support Space Wall Section

The walls of the support spaces are long and uneven. The layers created by the 3D printing process, the waving pattern, and the tapered slope are intended to emulate the layered walls of a canyon.



Support Space Isometric Section

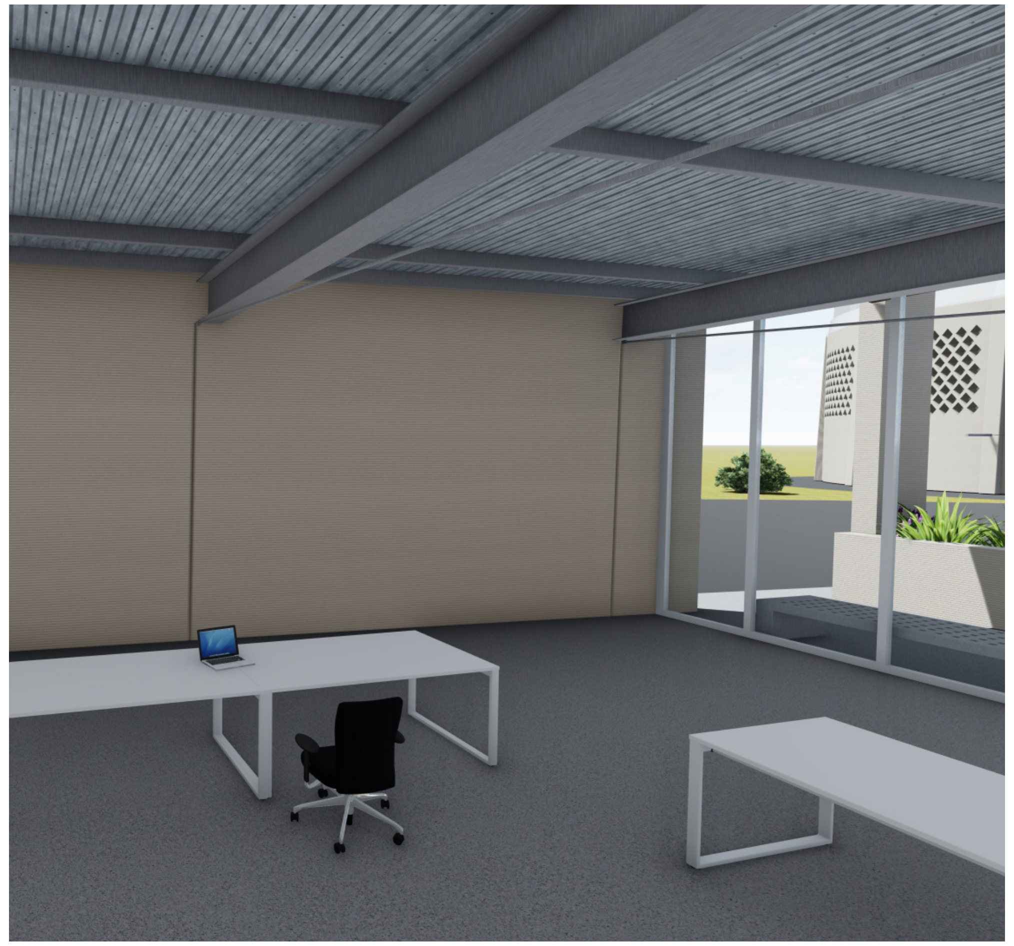


1: Reinforced Print Pattern Under Beam, Sill Plate Under Beam Embedded in Wall During Printing
2: Inverted King Truss @12ft Above Finished Floor
3: Vertical Groove Created from Reinforced Printing Pattern

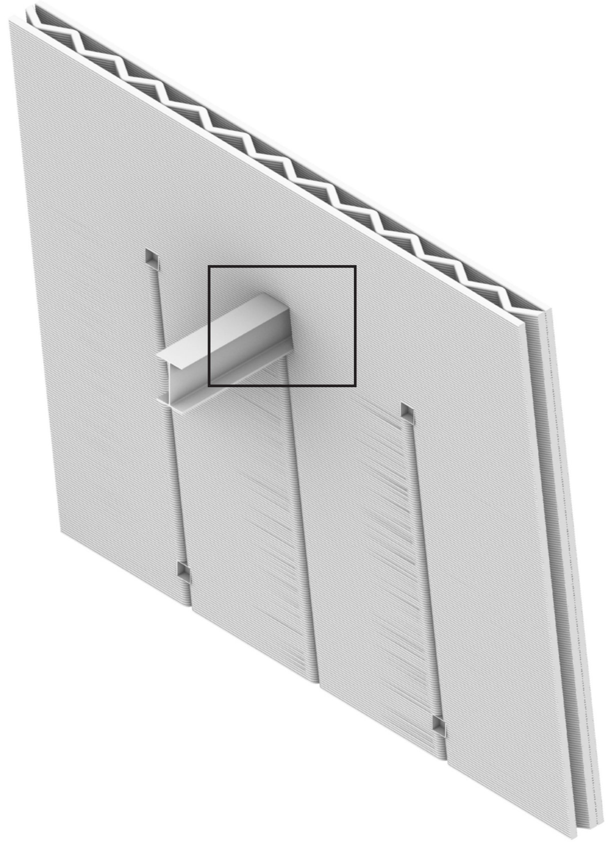
Beam to Wall Connection

Beam Support

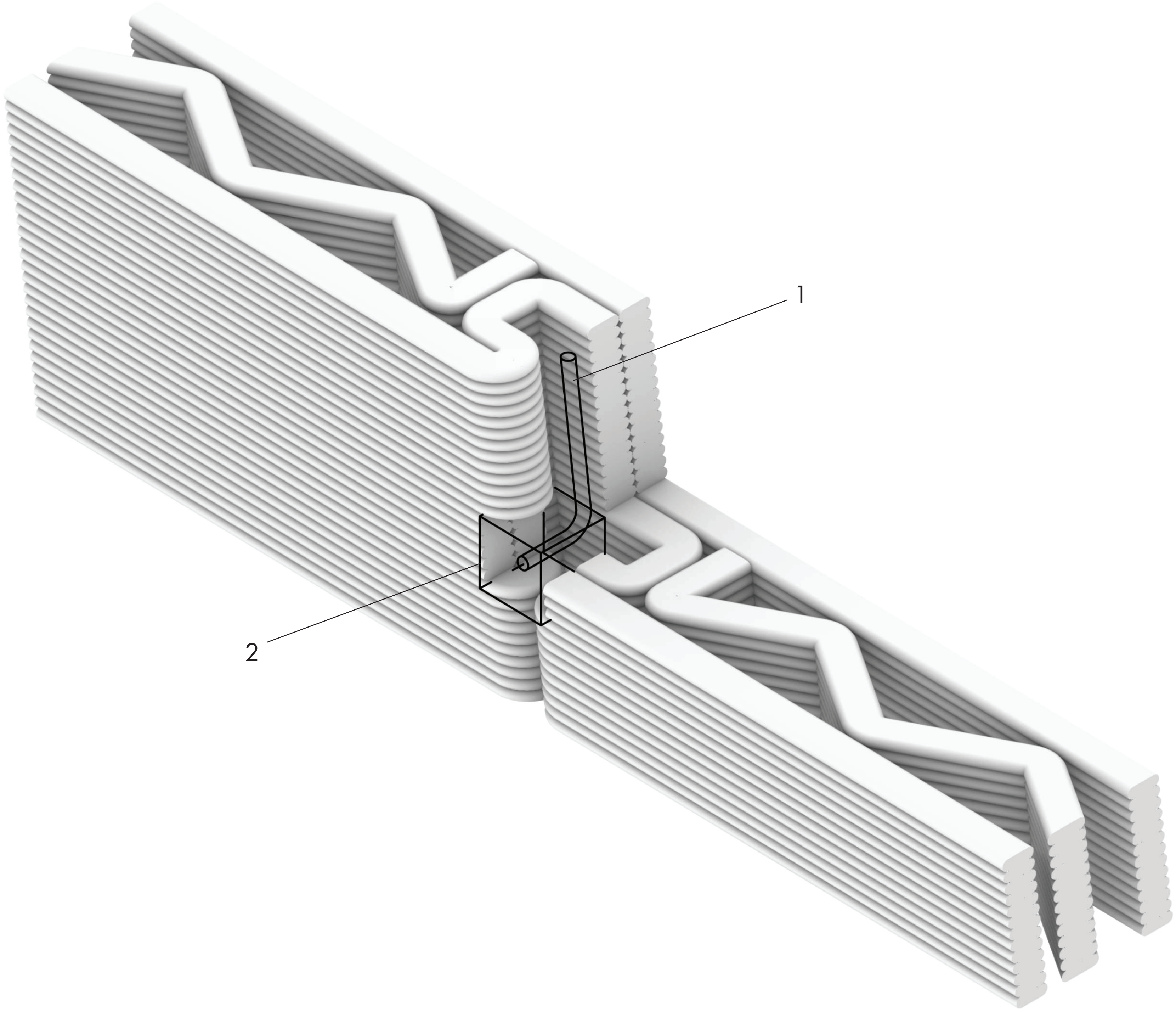
Each of the roof beams, inverted king trusses, will anchor into the wall of the support buildings. The wall print pattern is altered in this location, reinforcing the wall under the beam. This eliminates the need for additional structural elements in the wall, as the wall is able to become the primary structure. This reinforce pattern has the additional effect of creating a vertical groove in the wall leading up to the beams' location.



Render, inside office space



Location Key



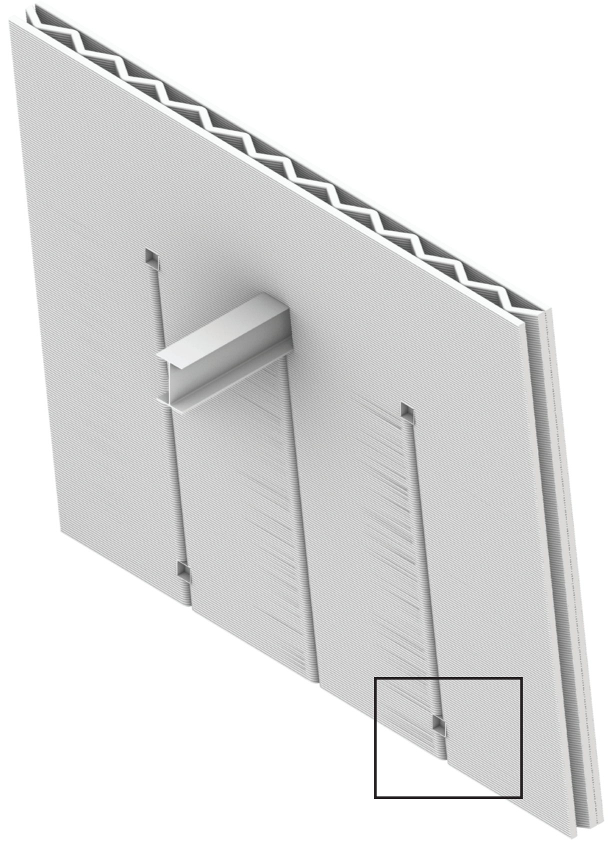
1: Conduit Run in Wall, Installed After Printing
2: Electrical Box, Installed During Printing, Outlets Added After

Electrical Outlets

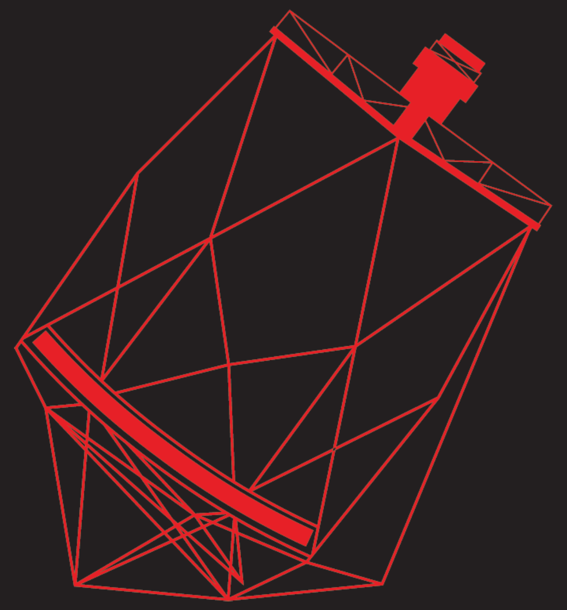
Electrical Integration

Electrical outlets are to be placed in the walls as they are being printed. This will require a small increase in labor, but will save time and labor in the long run as the work of electricians will reduce greatly.

Metal Electrical Outlet Box *Figure 53*



Location Key



BIBLIOGRAPHY

Bibliography:

- Barrett, K. (2022, November). *How 3D Printing in Construction Can Benefit the Industry. Construct Connect Blog.* Retrieved 2023, from https://www.constructconnect.com/blog/3d-printing-construction
- Beorkrem, C. (2017). *Material Strategies in Digital Fabrication* (2nd ed.). London, England: Routledge.
- Cabay, E., & Dubor, A. (2017). *TerraPerforma: 3D Printed Performative Wall.* IAAC. Retrieved 2023, from https://iaac.net/project/terraperforma/
- Cabay, E., & Dubor, A. (2019). *Building Architecture Continuity.* IAAC. Retrieved 2023, from https://iaac.net/project/building-architecture-continuity/
- Cabay, E., & Dubor, A. (2021). *IAAC designs and constructs Spain's first 3D printed building using earth and Crane WASP. IAAC.* Retrieved 2023, from https://iaac.net/project/3dpa-prototype-2022/
- Caneparo, L. (2016). *Digital Fabrication in Architecture, Engineering and Construction.* Dordrecht, Netherlands: Springer.
- Dunn, N. (2012). *Digital Fabrication in Architecture.* London, England: Laurence King Publishing.
- Ellis, G. (2020, August). *3D Printing in Construction: Growth, Benefits, and Challenges.* AutoDesk Construction Blog. Retrieved 2023, from https://constructionblog.autodesk.com/3d-printing-construction/
- Emre, M. (2022, July). *Apis Cor Completes The Dubai Municipality, Largest 3D-Printed Construction. Parmetric Architecture.* Retrieved 2023, from https://parametric-architecture.com/apis-cor-completes-the-dubai-municipality-largest-3d-printed-construction/
- *Hobby-Eberly Telescope. McDonald Observatory University of Texas.* (2017). Retrieved 2023, from https://mcdonald.utexas.edu/for-researchers/research-facilities/hobby-eberly-telescope
- Iwamoto, L. (2013). *Digital Fabrications.* Princeton Architectural Press.
- *Palo Duro Canyon State Park - Nature. Texas Parks & Wildlife.* (n.d.). Retrieved 2023, from https://tpwd.texas.gov/state-parks/palo-duro-canyon/nature
- *Palo Duro Canyon State Park Trail, Texas Climate Averages.* Weatherwx.com. (n.d.). Retrieved 2023, from https://www.weatherwx.com/climate-averages/tx/palo+duro+canyon+state+park+trail.html
- *Paranal Observatory. ESO.* (n.d.). Retrieved 2023, from https://www.eso.org/public/teles-instr/paranal-observatory/
- Perrot, A. (2019). *3D Printing of Concrete: State of the Art and Challenges of the Digital Construction Revolution.* ISTE.
- *TECLA Press Kit.* WASP. (2021). Retrieved 2023, from https://www.3dwasp.com/en/3d-printed-house-tecla/
- Tukiainen, M. (n.d.). *Amarillo, Texas, United States - Sun.* Gaisma. Retrieved 2023, from https://www.gaisma.com/en/location/amarillo-texas.html
- Zumthor, P. (2006). *Thinking Architecture (2nd ed.).* Birkhauser.

Image Sources:

Figure 1: - NASA Expedition 61 Crew (2020) Astronaut photograph ISS062-E-5419 [Photograph] NASA Earth Observatory
https://earthobservatory.nasa.gov/images/148276/smoke-in-the-stratosphere

Figure 2: - Erin (2022) The galactic core over Palo Duro Canyon [Photograph] Erin Outdoors
https://erinoutdoors.com/texas-stargazing/

Figure 3: - NRAO (2013) ALMA Control Room [Photograph] National Radio Astronomy Observatory (NRAO)
https://public.nrao.edu/gallery/alma-control-room/

Figure 4: - Buswell, R.A. (2018) Examples of 3DCP application type and orientation of the manufactured components [Inforgraphic] Cement and Concrete Research
https://www.sciencedirect.com/science/article/pii/S0008884617311924

Figure 5: - Corboy, P (2017) [The mobile 3D construction printer is the first of its kind] [Photograph] DesignBoom
https://www.designboom.com/architecture/apis-cor-pik-3d-printed-house-24-hours-02-28-2017/

Figure 6: - Cano, P (2022) [ICON, BIG, and Lennar 3D printing homes] [Photograph] ArchDaily, ICON Build
https://www.archdaily.com/992081/big-icon-and-lennar-announce-community-of-3d-printed-homes-in-texas-usa

Figure 7: - Gocha, A (2014) Recycled Concrete [Infrographic] The American Ceramic Society, Belatchew Arkitekter
https://ceramics.org/ceramic-tech-today/swimcity-floating-housing-project-uses-recycled-concrete-and-3d-printing-for-sustainable-solutions

Figure 8: - ICON Build (2021) Mars Dune Alpha, 3D printed by ICON, in progress at NASA's Johnson Space Center in Houston, Texas [Photograph] ICON Build
https://www.iconbuild.com/media-gallery/3d-printed-first-simulated-mars-surface-habitat-for-nasa

Figure 9: - Tweedie, E (2017) Hobby-Eberly Telescope [Photograph] University of Texas at Austin McDonald Observatory College of Natural Sciences
https://mcdonald.utexas.edu/for-researchers/research-facilities/hobby-eberly-telescope

Figure 10: - Harris, M (2011) Hobby-Eberly Telescope, Aerial View [Photograph] McDonald Observatory
https://mcdonaldobservatory.org/news/gallery/hobby-eberly-telescope-aerial-view

Figure 11: - Steinle, H (2011) HETDEX Collaboration [Digital Image] Max Planck Institute for Extraterrestrial Physics
https://www.mpe.mpg.de/3183412/C_K-20130919

Image Sources (Continued):

Figure 12: - Scoles, S (2017) McDonald Observatory [Photograph] WIRED
https://www.wired.com/2017/03/astronomers-dont-point-telescope-telescope-points/

Figure 13: - [Schematic diagram of the Hobby-Eberly Telescope] (2002) [Infographic] Penn State University
https://personal.psu.edu/wnb3/astro1/slideshows/class28/slides-28.html

Figure 14: - Hudepohl, G (2015) Aerial sunset over Paranal [Photograph] ESO
https://www.eso.org/public/images/potw1535a/

Figure 15: - *[Paranal Observatory]* (1999) [Photograph] ESO
https://www.eso.org/public/images/paranal_16-nov1999/

Figure 16: - Heye, H.H. (2014) *Paranal Platform After Sunset* [Photograph] ESO
https://www.eso.org/public/images/platform-to-northwest/

Figure 17: - *[Paranal Observatory – instruments]* (2009) [Infographic] ESO
https://www.eso.org/public/images/vlt/

Figure 18: - Hudepohl, G (2012) *The observing platform as the crow flies* [Photograph] ESO
https://www.eso.org/public/images/eso-paranal-33/

Figure 19: - Boncina, I (2010) *VLT at Paranal* [Photograph] ESO
https://www.eso.org/public/images/ib-paranal01/

Figure 20: - Corazza, I (2021) *TECLA house* [Photograph] It's Nice That
https://www.itsnicethat.com/news/tecla-house-mario-cucinella-wasp-architecture-270421

Figure 21- 23: - Cucinella, M (2019) *[TECLA Day and Night Renders]* [Render/Infrographic] School of Sustainability Foundation
https://www.schoolofsustainability.it/mario-cucinella-architects-and-wasp-start-on-site-with-tecla-a-prototype-3d-printed-global-habitat-for-sustainable-living/

Figure 24: - Costruzioni, E (2021) *TECLA 3D Printed House* [Photograph] WASP
https://www.3dwasp.com/en/3d-printed-house-tecla/

Figure 25 - 26: - Cabay, E & Dubor, A (2017) *TerraPerforma* [Infographic, Photograph] IAAC
https://iaac.net/project/terraperforma/

Figure 27 - 28: - Cabay, E & Dubor, A (2019) *Building Architecture Continuity* [Infographic, Photograph] IAAC
https://iaac.net/project/building-architecture-continuity/

Figure 29 - 30: - Cabay, E & Dubor, A (2021) *TOVA* [Infographic, Photograph] IAAC
https://iaac.net/project/3dpa-prototype-2022/

Figure 31 - 37: - Emre, M (2022) *Dubai Manucipility Apis Cor* [Photograph] Parametric Architecture
https://parametric-architecture.com/apis-cor-completes-the-dubai-municipality-largest-3d-printed-construction/

Figure 38 - 41: - Google (2023) *Armstrong County, TX* [Map Images] Google Earth
https://earth.google.com/

Figure 42: - *[Location of Texas in USA]* (2023) *Location map of the State of Texas in the US* [Map] NationsOnline.org
https://www.nationsonline.org/oneworld/map/USA/texas_map.htm

Figure 43: - *[Location of Armstrong County in TX]* (2006) *Armstrong County, TX* [Map] nationalatlas.gov
https://edcftp.cr.usgs.gov/pub/data/nationalatlas/countyp020.tar.gz

Figure 44: - Ligutti, S (2022) *Panorama of Fiery Sunset Over Lighthouse Rock - Palo Duro Canyon State Park - Texas Panhandle* [Photograph] Travel in USA
https://www.shutterstock.com/image-photo/panorama-fiery-sunset-over-lighthouse-rock-1403807783

Figure 45: - *[Palo Duro Canyon State Park]* (Accessed 2023) *Palo Duro Canyon State Park* [Photograph] Texas Parks & Wildlife
https://tpwd.texas.gov/state-parks/palo-duro-canyon

Figure 46: - Richter, S (2015) *Palo Duro as viewed from above* [Photograph] Houstonia - Travel & Outdoors
https://www.houstoniamag.com/travel-and-outdoors/2015/07/open-road-palo-duro-canyon-second-to-none

Figure 47: - Burgan, S (2013) P*alo Duro Canyon roadrunner* [Photograph] Flickr
https://www.flickr.com/photos/63339942@N00/8929483829/in/photostream/

Figure 48: - *[Playa on property]* (2021) [Format] Trulia
https://www.trulia.com/home/18801-S-Osage-St-Amarillo-TX-79118-250676661

Figure 49: - LightPolutionMap (2022) *VIIRS 2022 Overlay* [Map] lightpollutionmap.com
https://www.lightpollutionmap.info/

Figure 50: - Greebon, R (Accessed 2023) *Milky Way over Palo Duro Canyon 3* [Photograph] ImagesFromTexas.com
https://www.imagesfromtexas.com/photo/milky-way-over-palo-duro-canyon-3/

Figure 51: - Gorman, C (2020) *Stonehenge* [Photograph] WIRED
https://www.wired.com/story/archaeologists-have-found-the-source-of-stonehenges-boulders/

Figure 52: - *[Aluminum C Channel for LED Strip Lights]* (Accessed 2023) [Infographic] AliExpress
https://www.aliexpress.us/item/2251832264702516.html

Figure 53: - *[Electrical Box]* (Accessed 2023) [Photograph] Cooper Electric
https://www.cooper-electric.com/product/detail/35579/steel-city-kindorf-thomas-betts-72171-1