UNITED STATES DEPARTMENT OF COMMERCE
NATIONAL OCEANIC & ATMOSPHERIC ADMINISTRATION
NATIONAL OCEAN SERVICE
NATIONAL GEODETIC SURVEY

FOUNDATION CORS PROGRAM
LOCAL SITE SURVEY REPORT
LOCAL TIE INFORMATION REPORT
IERS NETWORK SITE: Pie Town, New Mexico (USA)

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Dates of Survey: March 16-28, 2026
Date of Report: June 2026

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Introduction

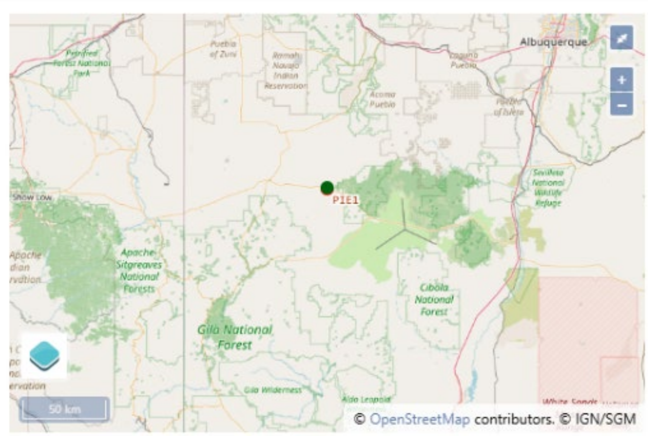
In March 2026, a high-precision local tie survey was conducted at the National Radio Astronomy Observatory (NRAO) facility near Pie Town, New Mexico. The site is an International Earth Rotation and Reference Systems Service (IERS) network site designated Pie Town. The station features co-located space geodetic technique (SGT) instruments that contribute directly to global realizations of the International Terrestrial Reference Frame (ITRF).

Space geodetic techniques at the site currently include Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite Systems (GNSS). GNSS station **PIE1** operates as a critical International GNSS Service (IGS) tracking network station and a National Geodetic Survey (NGS) Continuously Operating Reference Station (CORS). The co-located NRAO facility hosts an operational 25-meter radio telescope that serves as a core component of the Very Long Baseline Array (VLBA), with its structural center of rotation defined geodetically as the invariant point (**7234**). The geodetic footprint at the Pie Town facility represents a stable, tightly controlled tracking environment connecting fundamental astronomical and satellite-based reference frames.

The primary objective of this survey was to establish high-precision local tie vectors between the active space geodetic technique instruments and their primary local reference marks. Data collection consisted of highly redundant terrestrial observations executed with a high-precision robotic total station, alongside survey-grade static GNSS instrumentation. The resulting local geometric relationships were mathematically aligned to the current International Terrestrial Reference Frame at the epoch date of the survey, **ITRF2020 (2026/03/22)**. This report documents the instrumentation, observation configurations, mathematical reductions (including astrogeodetic vertical deflections and structural thermal corrections), analysis, and final three-dimensional adjustment results of the survey.

1. ITRF SITE INFORMATION

IERS site name: Pietown
IERS site number: 40456
Country name: United States of America
Surveying institution: National Geodetic Survey
Dates of survey: March, 2026
Longitude: W 108° 07’
Latitude: N 34° 18’
Tectonic plate: North American



DOMES 40456	Code/ 4-CID	Name	SGT Instrument	Description
S001	7234	Pietown VLBA	VLBA 25-meter	VLBA antenna reference point

M001	PIE1	PIE1	GNSS choke ring antenna	Concrete GPS pier JPL 4009 S

Table 1: Space Geodetic Technique (SGT) instruments located at the site

2 Instrumentation

2.1 Tacheometers, EDMI, theodolites

2.1.1 Description

Leica TS60, S/N 886928 (Total Station)
Leica TS60, S/N 897354 (Total Station)
Specifications:
Angular measurement uncertainty of instrument: +/- 0.5"
Combined uncertainty of distance measurement throughout instrument range: +/- 0.6 mm

2.1.2 Calibrations

Leica TS60, S/N 886928
Certified by Leica Geosystems AG Heerbrugg, Switzerland on 2019/09/04.

Leica TS60, S/N 897354
Certified by Leica Geosystems AG Heerbrugg, Switzerland on 2024/09/25.

2.1.3 Auxiliary equipment

Kestrel 5500 Weather Meter, S/N 2830093
Accuracy: Air temperature: +/- 0.50 C
Pressure: +/- 1.5 mbar / Relative Humidity: +/- 2%

2.1.4 Analysis software

Terrestrial observations and analysis were conducted with commercially available software Spatial Analyzer (version 2025.2.0916.2) from New River Kinematics. Least squares adjustments were conducted with commercially available software Star*Net (version 13.0.2.5829) from MicroSurvey. Coordinate transformations and SINEX generation were conducted with AXIS software from Geoscience Australia.

2.2 GNSS units

2.2.1 Receivers

Trimble Alloy, P/N: 109100-10, S/Ns: 5931R40031, 5922R40086, 5931R40027
Specifications for Static GPS Surveying: Horizontal: +/- 5 mm + 0.5 ppm RMS Vertical: +/- 5 mm + 1 ppm RMS

2.2.2 Antennas

Trimble GPS ground plane antenna, Zephyr Geodetic Model 3, P/N 115000.10, S/Ns: 1551008898, 1551008874, 1551014341

2.2.3 Analysis software

Data processing and analysis were conducted with NGS's Online Positioning User Service (OPUS) and OPUS Projects. OPUS Projects uses NGS's Program for Adjustment of GPS Ephemerides (PAGES) software as an underlying multi-baseline processing engine. Star*Net and

AXIS were also used in the analysis of GNSS data.

2.3 Leveling
No leveling instrumentation was used in this survey.

2.3.1 Leveling instruments
Not applicable.

2.3.2 Leveling rods
Not applicable.

2.4 Tripods
Wooden surveying tripods, with collapsible legs were, used to support surveying instrumentation. Fixed- height range poles with attached tripod support legs were used with target reflectors.

Surveying tripod for instrumentation

Fixed-height range pole

Fixed-height tripod

2.5. Forced-centering devices

Conventional Marks and Tripods

For traditional ground network marks, target reflectors were centered over marks using fixed-height range poles of a calibrated length. To ensure high-precision positioning, each range pole was verified for straightness and precisely plumbed over the mark using a calibrated precision bubble level.

Braced Monuments and SCIGN Mounts

Since the previous survey, new high-stability GNSS monuments have been installed across the sub-network. These include a Deep Drilled braced monument (PTV1), two Shallow Drilled braced monuments (PTV2 and PTV3), and a building-mounted monument (PTVB). The integrated forced-centering device for each of these monuments is a standard SCIGN antenna mount. These SCIGN mounts provided extremely rigid, repeatable forced-centering platforms, allowing the monuments to be directly and interchangeably occupied by the total station, GNSS antennas, and retro-reflectors throughout the main network scheme.

Multi-Technique Adapters (MTA)

To maximize observation efficiency and eliminate centering errors between different measurement phases, custom Multi-Technique Adapters (MTA) designed by the National Geodetic Survey were deployed on the braced monuments. The MTA attaches directly to the SCIGN mount and is engineered to permit the simultaneous collection of terrestrial and GNSS data. The lower tier of the adapter provides standard 5/8" x 11 threads to house a precision retro-reflector, while the upper platform securely elevates a GNSS antenna directly above it on the same vertical axis. This concurrent data collection strategy ensures absolute spatial correlation between the terrestrial and GNSS networks at the braced monuments.

SCIGN Mount at PTV2 with MTA and GNSS Antenna

2.6 Targets, reflectors

Leica Break Resistant 1.5-inch reflector, P/N 576-244
  Centering of Optics: < ± 0.01mm
Leica Reflector Holder 1.5-inch, P/N 577-104
  25mm vertical offset
Brunson Reflector Holder, 1.5THT-.625-11
Leica Tripod Adapter, P/N 575-837

Terrestrial observations were made to Leica 1.5-inch Break Resistant Reflectors, serving as both target and reflector. The reflectors occupied the marks using the forced-centering devices and adapters above.

2.7 Additional instrumentation

No additional instrumentation was used in this survey.

3 Measurement setups

3.1 Ground network

The site has a network of existing ground marks which were recovered during this campaign. The 25-meter VLBA radio telescope does not have an associated physical mark representing its conventional reference point. Therefore, the space geodetic technique's invariant point (7234) was observed indirectly using a 3D circle-fitting approach based on precise terrestrial observations to targets mounted on the telescope structure.

The reference point for the IGS station PIE1 (Pietown VLBA Site) was physically recovered. As described in the official site log and verified in the field, the monument consists of a 0.457 m diameter stainless steel plate set flush in the center of a 0.762 m diameter concrete monolith that projects 0.5 m above the ground. The specific reference point is defined as the small divot in the top-center of this plate. The GNSS antenna is mounted and centered precisely over this divot using a stainless steel mount secured to the concrete.

At the Pie Town NRAO site, the newly installed Deep Drilled and Shallow Drilled braced monuments

(PTV1, PTV2, PTV3) and the building-mounted monument (PTVB) were directly occupied for concurrent terrestrial and GNSS data collection using their integrated SCIGN mounts.

A previous local tie survey was conducted by NGS at the Pie Town site in 2016. The current 2026 survey successfully recovered and included main-scheme legacy marks from that previous survey (such as PTR1, PTR2, PTR3, PTR4 and PTR5) to provide a rigorous check on the historical consistency and stability of the site's ground marks and space geodetic techniques.

3.1.1 Listing

Current Survey	DOMES	IERS 4-char code	Previous Survey Point Name	NGS PID
Space geodetic technique stations				
PIETOWN VLBA CRP	40456S001	7234	VLBA REF PT (CDP 7234)	ER0695
PIETOWN CORS MONUMENT	40456M001	PIE1	PIETOWN CORS MONUMENT	AF9513
Ground network marks				
PTR1	--	PTR1	PIE TOWN VLBA RM1	ER0692
PTR2	--	PTR2	PIE TOWN VLBA RM2	ER0693
PTR3	--	PTR3	PIE TOWN VLBA RM3	ER0694
PTR4	--	PTR4	PIE TOWN VLBA RM4	--
PTR5	--	PTR5	PIE TOWN VLBA RM5	--
PTV1	--	n/a	--	--
PTV2	--	n/a	--	--
PTV3	--	n/a	--	--
PTVB	--	n/a	--	--

Table 2: Listing of SGT stations and ground network marks

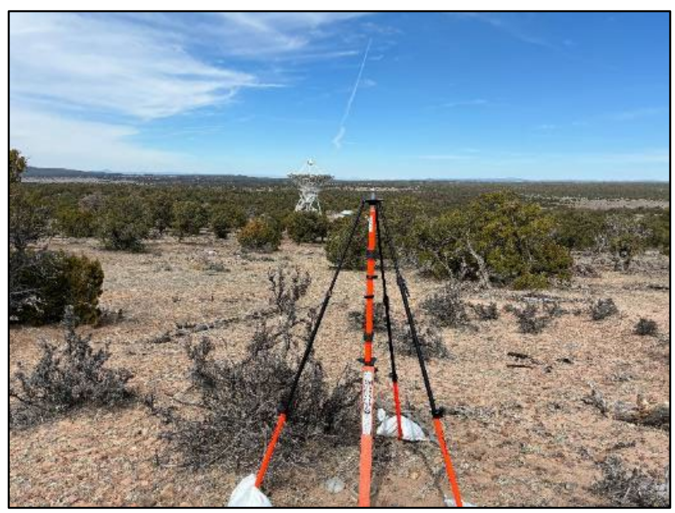
Ground network mark descriptions

PIE TOWN VLBA RM 1, PTR1

PTR1 is a National Aeronautics and Space Administration (NASA) reference mark established to serve the NRAO VLBA radio telescope. The mark is a dimple, set in the top center of a rounded stainless-steel rod inside a grease filled PVC sleeve. The setting depth of the rod and sleeve are unknown. The mark is set in the center of a PVC pipe with an aluminum logo cover. The aluminum logo cover is stamped PIE TOWN N.M. VLBA RM 1 8 90 7234.

PIE TOWN VLBA RM 2, PTR2

PTR2 is a NASA reference mark established to serve the NRAO VLBA radio telescope. The mark is a standard NASA-GSFC brass survey disk set flush in the top of a concrete post type monument and inside a PVC pipe with aluminum logo cover. The setting depth of the concrete post is unknown. The brass disk is stamped PIE TOWN NM VLBA RM 2. The aluminum logo cover is stamped PIE TOWN NM. VLBA RM2 7234 AUG 1990.



PIE TOWN VLBA RM 3, **PTR3**

PTR3 is a NASA reference mark established to serve the NRAO VLBA radio telescope. The mark is a dimple, cast in the top center of a NASA-SFC brass disk, set flush in the top of a concrete post type monument and inside a PVC pipe with aluminum logo cover. The setting depth of the concrete post is unknown. The brass disk is stamped PIE TOWN N.M. VLBA RM 3. The aluminum logo cover is stamped PIE TOWN N. M. VLBA RM 3 AUG 1990 7234.

PIE TOWN VLBA RM 4, **PTR4**

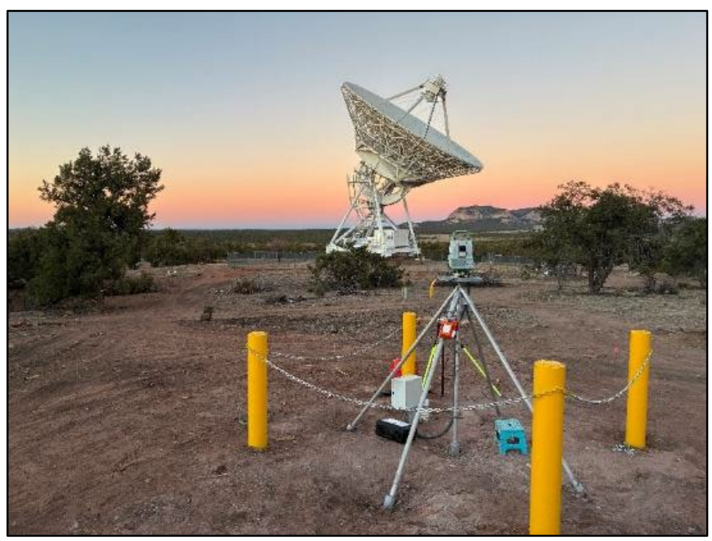
The mark is a dimple, cast in the top center of a NGS brass geodetic control disk, set flush in the top of a concrete post type monument set to a depth of 1.2 m. The disk is stamped PIE TOWN VLBA RM 4 2016.

PIE TOWN VLBA RM 5, **PTR5**

The mark is a dimple, cast in the top center of a NGS brass geodetic control disk, set flush in the top of a concrete post type monument set to a depth of 1.2 m. The disk is stamped PIE TOWN VLBA RM 5 2016.

PIE TOWN VLBA 1, PTV1

PTV1 is a newly established, high-stability Deep Drilled braced monument. The vertical point of reference is typical with the SCIGN mounts; a divot (8.3 mm) below the top plate. It is the reference mark for PTV1 GNSS antenna. The GNSS antenna was installed following observations. The monument is stamped “NOAA NGS PTV1 2025”.



PIE TOWN VLBA 2, PTV2

PTV2 is a newly established, high-stability Shallow Drilled braced monument. The vertical point of reference is typical with the SCIGN mounts; a divot (8.3 mm) below the top plate. The monument is stamped “NOAA NGS PTV2 2025”.

PIE TOWN VLBA 3, PTV3

PTV3 is a newly established, high-stability Shallow Drilled braced monument. The vertical point of reference is typical with the SCIGN mounts; a divot (8.3 mm) below the top plate. The monument is stamped “NOAA NGS PTV3 2025”.

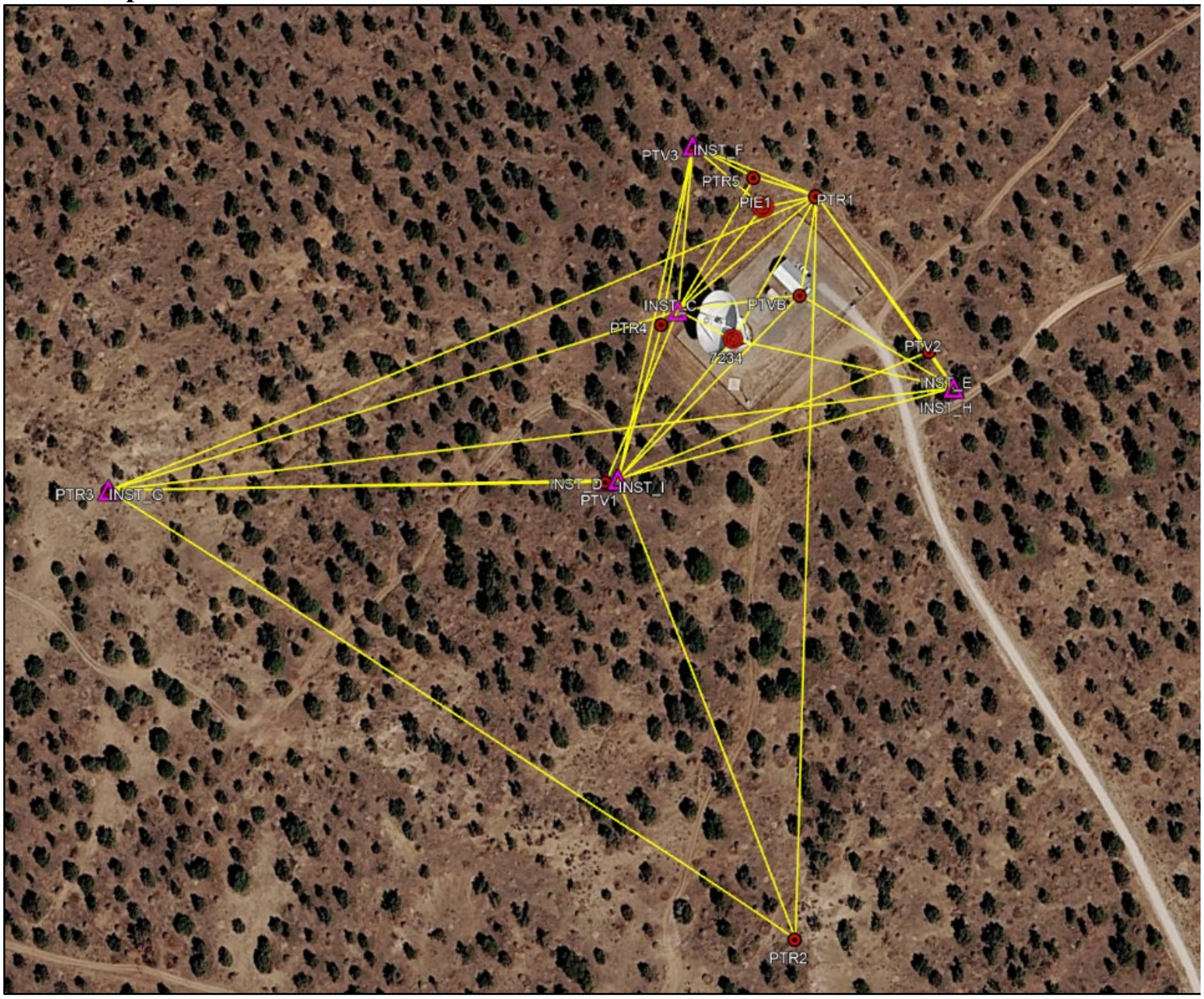
PTVB

PTVB is a newly established building-mounted monument located within the secure, fenced perimeter of the Pie Town NRAO VLBA site. The monument consists of a rigid metal pipe securely anchored to the brick wall of the operations building. The mast is topped with an integrated SCIGN antenna mount, which provides precision forced-centering for both terrestrial retro-reflectors and GNSS antennas. During the 2026 survey, the Topcon 762-13651 antenna and radome were removed in order to place a retroreflector for terrestrial observations. The antenna was replaced following our survey.

PIETOWN CORS MONUMENT, PIE1

The Instrument Reference Mark (IRM) is a dimple cast into the top center of a stainless steel plate set in the top center of a concrete pier set to a depth of 3.0 m. The plate is inscribed VLBA SITE GPS STATION MARK JPL 4009-S 1992.

3.1.2 Map of network

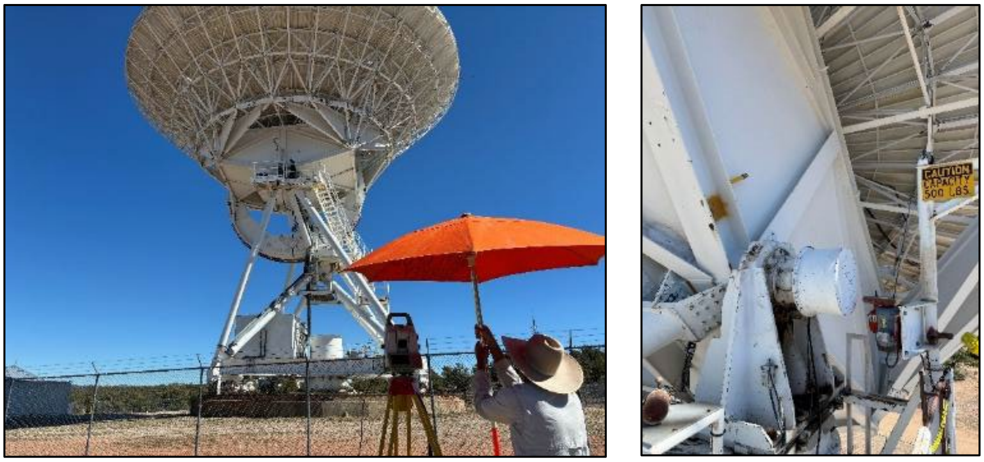


Pie Town VLBA

3.2 Representation of technique reference points

3.2.1 VLBI

7234 (Pie Town VLBA) is an active 25-meter VLBI radio telescope operated by the National Radio Astronomy Observatory (NRAO). This instrument is represented by a theoretical point in space: the invariant point (IVP) about which the azimuth and elevation axes rotate. Because the IVP cannot be physically occupied, an indirect approach was used to compute its position. Temporary targets were securely affixed to the telescope structure and tracked with the TS60 total station as they scribed circles about both the azimuth and elevation axes.



7234 and Magnetic Mounted Reflector

3.2.3 GNSS

The site hosts a single historical GNSS technique instrument that contributes to the International Terrestrial Reference System (ITRS).

PIE1 The National Aeronautics and Space Administration's Jet Propulsion Laboratory operates the GPS tracking station. The station is included in the International GNSS Service (IGS) tracking network. The antenna type at time of this survey was an Ashtech model ASH701945E_M NONE (S/N CR520022114). The Antenna Reference Point (ARP) is reported by the IGS to be centered horizontally over the IRM, with a vertical offset of 0.061 m.

Without removal of the antenna, the Instrument Reference Mark (IRM) is not accessible for direct occupation of survey instrumentation. The antenna was not removed this survey and the eccentricities were not able to be verified. An indirect approach was used to determine the GNSS reference point in the survey. A site log for PIE1 is available at the IGS web page:

https://files.igs.org/pub/station/log/pie100usa_20260325.log

PIE1

4 Observations

4.1 Terrestrial survey

The terrestrial survey of the Pie Town NRAO facility was performed utilizing a Leica TS60 high-precision robotic total station. This instrument recorded precise horizontal directions, zenith angles, and slope distances to high-precision retro-reflector targets to position the local ground monument network and indirectly determine the space geodetic technique invariant point (IVP) representing the geometric center of the 25-meter radio telescope (7234).

To resolve the mathematical relationship between the local astronomic plumb line (the true gravity vector) and the ellipsoidal normal of the satellite-based reference frame, the Total Station Astrogeodetic Control System (TSACS) was deployed. TSACS is an automated hardware and software suite designed to direct a robotic total station to track and image a predefined distribution of bright stars. The resulting data provides direct measurements of the Deflection of the Vertical (DoV), which prevents vertical angular errors from bleeding into the horizontal components of a high-precision combined 3D adjustment. During this campaign, TSACS successfully gathered automated stellar imagery over multiple sessions centered on the local network mark PTV1.

As part of the routine terrestrial observation scheme, all horizontal directions, zenith angles, and slope distances across the local network were observed with a minimum of three full sets. Double-centering was strictly enforced by measuring in both the direct and reverse instrument faces (Face I and Face II) to eliminate internal systematic mechanical, optical, and standing axis tilt errors. Meteorological data including ambient temperature, atmospheric pressure, and relative humidity was continuously monitored at the active total station setups, and precise parts-per-million (PPM) atmospheric refraction corrections were dynamically applied to all Electronic Distance Measurement (EDM) slope distances at the time of data collection.

Instrument setups (INST_C through INST_I) were established utilizing wooden tripods to construct a highly redundant line-of-sight skeleton across the facility. Terrestrial ground marks including the primary reference marks PTR1 through PTR5, PTV1 through PTV3, and the peripheral mark PTVB were occupied using precision retro-reflector targets carefully centered and leveled over the physical monuments using optical plummets and calibrated fixed-height apparatuses to minimize centering errors.

Data recording and field-level quality control checks were managed using digital data collection software to monitor angular closures and distance variances in real time. Final network validation, multi-technique vector integration, and three-dimensional least-squares adjustments were performed using MicroSurvey StarNet software. The finalized combined adjustment successfully integrated the terrestrial total station sets, static GNSS vectors, and corrected astrogeodetic DoV components, passing the global Chi-Square test at the 5.00% level with a balanced Total Error Factor of 1.003. A comprehensive accounting of the adjusted positions, standardized residuals, and full error propagation is preserved within the finalized StarNet .lst output file.

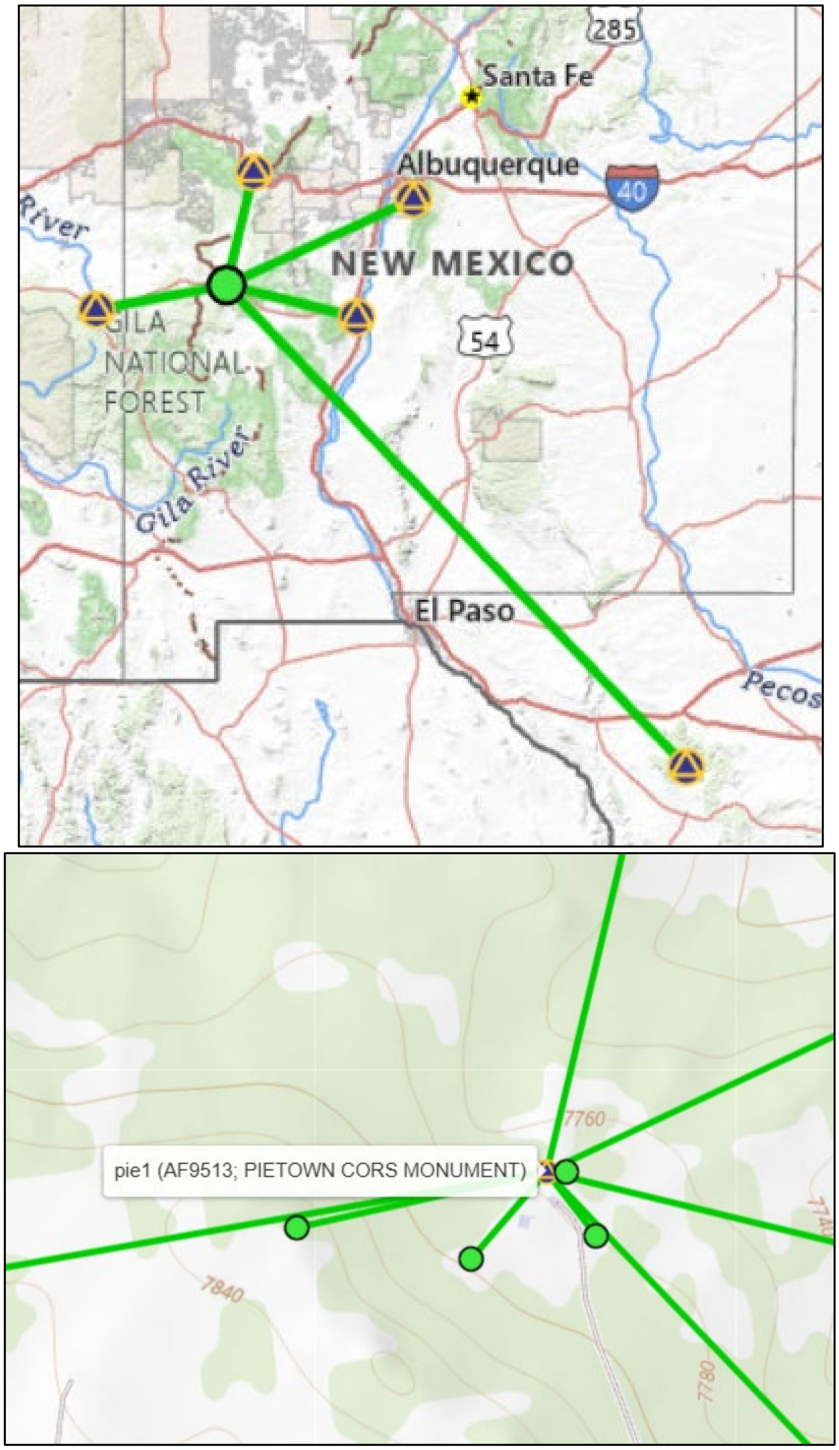
DoV observation using TSACS

4.2 Leveling
No leveling was conducted for this survey.

4.3 GNSS
GNSS data was collected to generate 3-dimensional ITRF2020 vectors between the local Pie Town network marks and regional stable reference stations at the epoch date of the survey, **ITRF2020 (2026/03/22)**. Over a campaign window spanning from **March 17, 2026, to March 28, 2026**, continuous long-session static observations were captured at the permanent **PIE1** tracking monument alongside local main-scheme marks. Publicly available observation data was also obtained for the active PIE1 PIETOWN CORS and several regional CORS, including **MDO1**, **AZRV**, **P107**, **P034**, and **SC01**.

The GNSS observations were processed within a multi-baseline network design using the Program for Adjustment of GPS Ephemerides (PAGES) baseline processing engine inside the NGS OPUS Projects software suite (Version 5.3.0). Highly precise ITRF2020 space-geodesy vectors connecting the regional CORS network to the local Pie Town facility were resolved utilizing final precise ITRF2020 satellite orbits and fully calibrated antenna phase center models.

Following baseline processing, a rigorous three-dimensional least-squares network adjustment of the satellite observations was executed. The finalized GNSS configuration yielded **231 GPS vector deltas** spanning the multi-day tracking sessions. The resulting GNSS coordinate solutions and their fully populated variance-covariance matrices were exported and integrated directly into the Star*Net combined network adjustment as G1 baseline records. This mathematical integration provides the rigid spatial anchor required to seamlessly align the local terrestrial total station sets to the global ITRF2020 reference frame without distorting the internal geometry of the ground network.



GNSS Network Diagram

4.4 General comments

Due to localized infrastructure and severe line-of-sight obstructions surrounding the 25-meter VLBA radio telescope, a hybrid network configuration was deployed for the Pie Town campaign. The total station heavily utilized the resection principle (free-stationing) from seven highly stable, arbitrary locations designated INST_C through INST_I. Crucially, the survey team also executed a direct instrument occupation at the primary main-scheme legacy ground monument, PTR1. This direct occupation provided high-leverage geometric lines of sight to the telescope structural tracking targets (7234), adjacent pillars, and control stations, significantly reinforcing the scale and orientation integrity of the terrestrial network.

The remaining ground monuments—including reference marks PTR2 through PTR5, PTV1 through PTV3, and the auxiliary tie mark PTVB—were observed using precision retro-reflector targets plumbed over the physical marks. At each instrument location, a highly redundant series of three-dimensional direct and reverse measurements were recorded to eliminate internal systematic errors. By rigorously linking these common targets across the various free stations and the direct occupation at mark PTR1, the spatial relationships of the entire terrestrial network were established within a unified MicroSurvey Star*Net 3D least-squares adjustment, which seamlessly integrated all datasets and successfully passed the global Chi-Square test with a balanced Total Error Factor of 1.003.

Establishing points via circle-fitting

The coordinates of the VLBA instrument's Invariant Point (IVP) were determined using an indirect approach of 3D circle fitting (Jean-Claude Poyard et al., 2017, p. 27). The "circle-fit" theory is briefly described as follows: A target, as it revolves about an axis, scribes an arc. That arc defines a circle and a plane simultaneously. The mechanical axis can then be mathematically defined as the line that passes through the center of the circle, orthogonal to the plane. By assigning coordinates to the points observed along an arc rotated about an axis, one can assign precise spatial parameters to the axis relative to the local ground coordinate system.

During the survey, total station measurements projected coordinates from the local ground network to retro-reflectors temporarily attached to the 25-meter VLBA telescope structure as it moved about its axes, thereby providing the necessary information to locate a single axis in space. The same procedure was performed for the opposing axis of the instrument in the exact same local reference frame. The unique point along the azimuth axis that is orthogonal to the elevation axis represents the VLBA technique's Invariant Point (7234).

Precise observations involving targets secured to the VLBA, combined with measurements taken from multiple instrument occupations and numerous measurements per axis, ensured that a sub-millimeter level of positional precision was achieved for the IVP determination.

5 Data analysis and results

5.1 Terrestrial survey

5.1.1 Analysis software

After data collection, Spatial Analyzer software was used to generate points and lines via the 3D circle-fitting routines described in the previous section. This spatial analysis allowed for the precise determination of the 25-meter VLBA technique's azimuth axis, elevation axis, axial offset, and ultimate

Invariant Point (IVP). Terrestrial observations of the ground network marks and the computed VLBA IVP were exported from Spatial Analyzer and imported into MicroSurvey Star*Net software. There, they were combined with the OPUS Projects GNSS vectors for a rigorous, three-dimensional least squares network adjustment. This combined geodetic adjustment produced the final ITRF2020 coordinates and variance-covariance information for all surveyed features. All adjustment parameters, statistical summaries, and positional results are available in the Star*Net `.lst` output file.

5.1.2 Thermal Expansion

The reference point of the 25-meter VLBA telescope (7234) is defined by its mechanical axes, which are subject to vertical displacement due to the thermal expansion and contraction of the antenna's concrete pedestal and steel structure. Because geodetic coordinates published in the ITRF are referenced to a standard temperature (established explicitly as 7.7°C for SGT 7234), terrestrial measurements taken at differing field temperatures must be corrected to account for this structural deformation.

The specific physical dimensions of the Pie Town 25-meter VLBA antenna (such as the height of the concrete foundation and the steel mount) and their respective material thermal expansion coefficients used to compute these corrections were sourced from the official International VLBI Service for Geodesy and Astrometry (IVS) `antenna-info.txt` file. The current antenna-info.txt file is available through the referenced IVS/TU Wien research data repository https://researchdata.tuwien.at/records/e9axk-3kr82

To ensure maximum rigor in the final adjustment, thermal expansion corrections were calculated for the specific environmental conditions present during the TS60 observations of the VLBA axes. These corrections were applied directly within the MicroSurvey Star*Net `.dat` files as highly precise vertical target height offsets applied to the 7234 Invariant Point (IVP) observations.

As documented in the `PIE101.lst` output file, the specific thermal expansion target height corrections applied during each independent instrument occupation were:

- **INST_B:** +0.00073 m
- **INST_C:** +0.00135 m
- **INST_H:** +0.00201 m
- **INST_I:** +0.00243 m

By applying these millimeter corrections directly to the target heights at the observation level, the Star*Net adjustment properly reduced the VLBA's physical geometry to the 7.7°C reference temperature before generating the final 3-dimensional Cartesian coordinates for the space geodetic technique.

7234 VLBI at Inst_B		
Celsius T0	7.7	Reference temperature (C).
c_foundation	0.000010	Coefficient of expansion of foundation material. Concrete, with 6 hour lag time.
c_pedestal	0.000012	Coefficient of expansion of pedestal/antenna material. Steel, with 2 hour lag time.
h_foundation	0.5	Dimension of foundation (m).
h_pedestal	13.7	Dimension of pedestal (m).

Observed Temperatures		
T_foundation	3.63	Six hours before optical survey observations
T_pedestal	12.25	Two hours before optical survey observations
Calculations	**Δh_total = Δh_foundation + Δh_pedestal**	
Δh_total	**0.00073**	
7234 VLBI at Inst_C		
Celsius T0	7.7	Reference temperature (C).
c_foundation	0.000010	Coefficient of expansion of foundation material. Concrete, with 6 hour lag time.
c_pedestal	0.000012	Coefficient of expansion of pedestal/antenna material. Steel, with 2 hour lag time.
h_foundation	0.5	Dimension of foundation (m).
h_pedestal	13.7	Dimension of pedestal (m).
Observed Temperatures		
T_foundation	7.51	Six hours before optical survey observations
T_pedestal	15.9	Two hours before optical survey observations
Calculations	**Δh_total = Δh_foundation + Δh_pedestal**	
Δh_total	**0.00135**	

7234 VLBI at Inst_H		
Celsius T0	7.7	Reference temperature (C).
c_foundation	0.000010	Coefficient of expansion of foundation material. Concrete, with 6 hour lag time.
c_pedestal	0.000012	Coefficient of expansion of pedestal/antenna material. Steel, with 2 hour lag time.
h_foundation	0.5	Dimension of foundation (m).
h_pedestal	13.7	Dimension of pedestal (m).
Observed Temperatures		
T_foundation	12.3	Six hours before optical survey observations
T_pedestal	19.8	Two hours before optical survey observations
Calculations	**Δh_total = Δh_foundation + Δh_pedestal**	
Δh_total	**0.00201**	

7234 VLBI at Inst_I		
Celsius T0	7.7	Reference temperature (C).
c_foundation	0.000010	Coefficient of expansion of foundation material. Concrete, with 6 hour lag time.
c_pedestal	0.000012	Coefficient of expansion of pedestal/antenna material. Steel, with 2 hour lag time.
h_foundation	0.5	Dimension of foundation (m).
h_pedestal	13.7	Dimension of pedestal (m).

Observed Temperatures		
T_foundation	13.42	Six hours before optical survey observations
T_pedestal	22.28	Two hours before optical survey observations
Calculations	**Δh_total = Δh_foundation + Δh_pedestal**	
Δh_total	**0.00243**	

5.1.3 Topocentric coordinates and covariance

The terrestrial survey was aligned to ITRF2020 (epoch date of survey) using the GNSS observations in a combined geodetic adjustment. AXIS software was used to compile topocentric coordinate estimates with station **PIE1** as the local origin. Complete covariance information for all network stations is available in AXIS .AXS output file.

Surveyed topocentric coordinates, ITRF2020 (epoch 2026/03/22)						
STATION	***E(m)***	***N(m)***	***U(m)***	***SE(m)***	***SN(m)***	***SU(m)***
Space geodetic technique stations						
PIE1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7234	-24.2651	-54.2532	16.9507	0.0003	0.0002	0.0010
Ground network marks						
PTR1	24.0165	0.2764	-1.3868	0.0001	0.0001	0.0003
PTR2	-48.0758	-311.5676	23.7493	0.0004	0.0002	0.0009
PTR3	-299.3125	-66.5073	23.4646	0.0001	0.0003	0.0007
PTR4	-53.5353	-41.5105	1.3994	0.0001	0.0001	0.0003
PTR5	-1.2362	13.6915	-1.1861	0.0001	0.0001	0.0003
PTV1	-90.6860	-104.2650	7.0391	0.0001	0.0002	0.0004
PTV2	59.4473	-75.8970	-0.5551	0.0001	0.0001	0.0004
PTV3	-25.0257	32.7624	-2.5902	0.0001	0.0001	0.0004
PTVB	8.5469	-40.9688	6.6066	0.0001	0.0001	0.0003

Table 3 Topocentric Coordinates

5.1.4 Correlation matrix

Complete correlation matrix information for all network stations can be found in AXIS ***.AXS*** output file.

5.2 GNSS

5.2.1 Analysis software

NGS's OPUS Projects software was used to process and analyze ITRF2020 vectors between stations at the epoch date of survey. As noted, Star*Net software was used to combine the terrestrial and GNSS observations in a rigorous least squares adjustment. The combined geodetic adjustment produced coordinates and variance-covariance information. Adjustment parameters and results are available in Star*Net ***.LST*** output file.

5.2.2 Results

AXIS was used to compile geocentric coordinate estimates from the combined geodetic adjustment. Using the GNSS observations, the survey was aligned to the reference frame ITRF2020 (epoch data of survey). Complete covariance information for all network station is available in AXIS ***.AXS*** output file.

Surveyed geocentric coordinates, ITRF2020 (epoch 2026/03/22)						
STATION	***X(m)***	***Y(m)***	***Z(m)***	***SX(m)***	***SY(m)***	***SZ(m)***
Space geodetic technique stations						
7234	-1640954.1180	-5014816.0067	3575411.7143	0.0004	0.0008	0.0006
PIE1	-1640917.1931	-5014781.1864	3575446.9794	0.0000	0.0000	0.0000
PTR1	-1640893.9628	-5014787.4184	3575446.4262	0.0001	0.0002	0.0002
PTR2	-1641023.5910	-5014951.7579	3575202.9824	0.0005	0.0007	0.0006
PTR3	-1641219.3477	-5014742.1471	3575405.2622	0.0002	0.0006	0.0005
PTR4	-1640975.7083	-5014787.8693	3575413.4769	0.0001	0.0003	0.0002
PTR5	-1640915.6637	-5014772.5375	3575457.6213	0.0001	0.0002	0.0002
PTV1	-1641023.4639	-5014814.3551	3575364.8147	0.0002	0.0003	0.0002
PTV2	-1640873.8526	-5014839.8888	3575383.9693	0.0001	0.0003	0.0002
PTV3	-1640934.5705	-5014753.8224	3575472.5842	0.0002	0.0003	0.0002
PTVB	-1640917.9474	-5014810.9744	3575416.8589	0.0001	0.0003	0.0002

Table 4: Coordinate estimates for network stations

5.3 Additional parameters

VLBI telescope axial offsets

In theory, the VLBI telescope's azimuth and elevation axes intersect. The survey observations were used with Spatial Analyzer software to determine any offset between the axes.

7234 offset: 2.1452 m +/- 1.6. mm

For 7234, the International VLBI Service reports an axial offset of 2.1375 m.

At the time of writing, file antenna-info.txt is available online.
https://researchdata.tuwien.at/records/e9axk-3kr82

Previous antenna-info.txt records report the following axial offsets:
7234 offset 2020: 2.1375 m
7234 offset 2014: 2.1377 m
7234 offset pre-2008: 2.1377 m

The previous NGS survey of this site reports an axial offset:
7234 offset 2016: 2.1380 m

5.4 Transformations

ITRF2020 GNSS vectors were generated to CORS in the surrounding region. The vectors were used in a combined geodetic adjustment to align, or transform, the surveyed local ties to ITRF2020 at the epoch date of survey.

5.5 Description of SINEX generation

AXIS software was used to generate a SINEX file with full variance-covariance matrix information. All stations with DOMES numbers are included in SINEX file **NGSPIE12603GA.snx.**

The following SINEX file naming convention was used.
XXXNNNNYYMMFV.SNX
Where:
XXX is a three-character organization designation.
NNNN is a four-character site designation.
YY is the year of the survey.
MM is the month of the survey.
F is the frame code (G for global, L for local).
V is the file version.

5.6 Discussion of results

A geodetic least squares adjustment of the observations was conducted using Star*Net. The statistical summary from the adjustment is included. For additional details concerning the adjustment, see Star*Net .LST output file.

Adjustment Statistical Summary
==============================

Iterations	=	3
Number of Stations	=	23
Number of Observations	=	1110
Number of Unknowns	=	124
Number of Redundant Obs	=	986

Observation	Count	Sum Squares of StdRes	Error Factor
Coordinates	3	0.000	0.000
Directions	295	269.031	1.013
Distances	287	258.943	1.008
Zeniths	294	258.937	0.996
GPS Deltas	231	205.980	1.002
Total	1110	992.891	1.003

The Chi-Square Test at 5.00% Level Passed
Lower/Upper Bounds (0.956/1.044)

Comparison with IERS computed tie

ITRF2020 (epoch date of survey) computed coordinates were obtained from the IERS. A comparison of the surveyed tie vectors against the computed ties is provided where available.

IERS geocentric computed coordinates, ITRF2020 (epoch 2026/03/22)			
STATION	***X (m)***	***Y (m)***	***Z (m)***
PIE1	-1640917.1943	-5014781.1866	3575446.9785
7234	-1640954.1230	-5014816.0170	3575411.7164

Table 5: IERS computed coordinates

Surveyed tie vs. IERS computed tie			
NGS 2026 geocentric tie discrepancies			
STATION	***X (mm)***	***Y (mm)***	***Z (mm)***
PIE1	1.2	0.2	0.9
7234	5.0	10.3	-2.1

Table 6: Tie discrepancies between surveyed and computed ties (surveyed minus computed)

Comparing ITRF2020 computed coordinates of SGTs, the current survey has a maximum tie discrepancy of 10.3 millimeters in the Y component for 7234.

5.7 Comparison with previous surveys

As a check on the results of the field survey, AXIS software was used to align the current survey to the NGS 2016 previous survey in ITRF2008 (epoch 2016/05/18). Topocentric tie vector comparisons are provided for all common surveyed stations. Complete coordinate information is available in the included data products.

Surveyed ties vs. Previous survey (NGS 2016)			
Topocentric tie discrepancies			
STATION	***DE (mm)***	***DN (mm)***	***DU (mm)***
PIE1	0.0	0.0	0.0
7234	0.1	0.3	-0.5
PTR1	0.0	0.4	-0.2
PTR2	0.5	0.3	0.4
PTR3	0.1	-0.3	-0.7
PTR4	0.1	0.2	-0.1
PTR5	0.1	0.2	-0.1

Table 7: Tie discrepancies between current survey and previous survey (current minus previous)

6 Planning aspects

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Recommendations

Provide NRAO with a full list of contacts, schedule, and description of survey schedule as part of a comprehensive visitor safety plan during the planning phase.

Configure equipment and all personal communication devices to not emit RF interference unless specific times are coordinated ahead of time (e.g. Wi-Fi, cellular, Bluetooth).

7 References

7.1 Name of person(s) responsible for observations

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7.3 Location of observation data and results archive

National Geodetic Survey
672 Independence Parkway
Chesapeake, VA 23320
Phone: 202-384-6471

7.4 Works referenced

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