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

FOUNDATION CORS PROGRAM
LOCAL TIE INFORMATION REPORT
IERS NETWORK SITE: Mauna Kea, HI (USA)

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John May

Date of Survey: January 2020
Date of Report: May 2020

Introduction

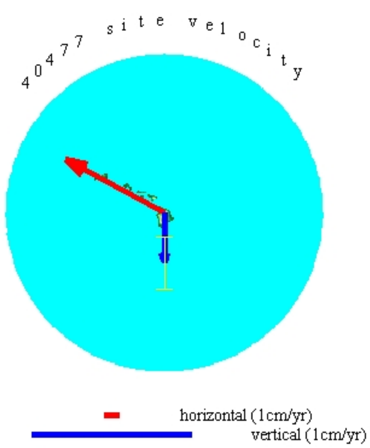
In January 2020, the National Geodetic Survey (NGS) conducted a local tie survey at the International Earth Rotation and Reference Systems Service (IERS) Maua Kea site (Mauna Kea VLBA Observatory). This site features co-located space geodetic technique (SGT) instruments that contribute to realizations of the International Terrestrial Reference Frame (ITRF).

Space geodetic techniques at this site include Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite Systems (GNSS). VLBI observations are conducted via a 25-meter radio telescope, operated by the National Radio Astronomy Observatory as part of the Very Long Baseline Array (VLBA). GNSS observations are conducted via a GNSS station, operated by the NASA Jet Propulsion Laboratory (JPL). The GNSS station is an International GNSS Service (IGS) tracking network station and the NGS Continually Operating Reference Station (CORS). It has been identified by NGS as a Foundation CORS.

The primary objective of the survey was to determine high-precision local tie vectors between the VLBI technique 7617, the GNSS technique MKEA, and their associated reference marks. Data collection consisted of terrestrial observations with an absolute laser tracker system and GNSS observations with survey-grade instrumentation. The local relationships were aligned to the current International Terrestrial Reference Frame at the epoch date of survey, ITRF2014 (2020/01/19). This report documents the instrumentation, observations, analysis, and results of the survey.

1 Site description

IERS site name: Mauna Kea
IERS site number: 40477
Country name: United States of America
Surveying institution: National Geodetic Survey
Dates of survey: January 15 - 23, 2020
Longitude: E 204° 33’
Latitude: N 19° 48’
Tectonic plate: Pacific



Geodetic Technique	Name	DOMES#	ITRF Description
GNSS	MKEA	40477M001	GPS MARKER
VLBI	7617	40477S001	25-M VLBA antenna reference point

Table 1: ITRF site information for space geodetic technique instruments

2 Instrumentation

2.1 Tacheometers, EDMI, theodolites

2.1.1 Description

Leica AT402, S/N 392045 (absolute laser tracker system)
Specifications:
Angular measurement uncertainty of instrument: +/- 0.5”
Combined uncertainty of distance measurement throughout instrument range: +/- 0.014 mm

2.1.2 Calibrations

Leica AT402, S/N 392045
Certified by Leica Geosystem AG Heerbrugg, Switzerland on 2013/08/28.

2.1.3 Auxiliary equipment

Leica ATC meteo-station, S/N D214.00.000.002
Accuracy:
Air temperature: +/- 0.30 C
Pressure: +/- 1 hPa
Relative Humidity: +/- 5%

2.1.4 Analysis software

Terrestrial observations and analysis were conducted with commercially available software Spatial Analyzer (version 2019.05.16_55321) from New River Kinematics. Least squares adjustments were conducted with commercially available software Star*Net (version 9,1,4,7868) from MicroSurvey. Coordinate transformations and SINEX generation were conducted with AXIS software from Geoscience Australia.

2.2 GNSS units

2.2.1 Receivers

Trimble NetR5, P/N: 67668-30, S/Ns: 5832R50297, 5820R50154, 5832R50274
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 115000-00, S/Ns: 6122223928, 1441037967, 6122223766

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.

2.3.3 Checks carried out before measurements

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 and GNSS antennas. At some stations, a “multipurpose tripod adapter” (MTA) was used with a fixed-height range pole to mount target reflectors and GNSS antennas simultaneously.

Surveying tripod for instrumentation

Fixed-height range pole

2.5 Forced-centering devices

Target reflectors and GNSS antennas were centered over marks using fixed-height range poles of known length. Each range pole was verified to be straight and was plumbed over the mark with a precision bubble level.

Forced-centering device to occupy a mark

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 setup

3.1 Ground network

In addition to the two space geodetic techniques, the site has several existing ground marks which were recovered.

3.1.1 Listing

Current Survey	DOMES	IERS 4-char code	Previous Survey Point Name	NGS PID
SGT geometric reference points				
MKEA	40477M001	MKEA	MKEA	DE6591
7617	40477S001	7617	7617	n/a
Ground network marks				
7617 RM1	n/a	n/a	7617 RM1	n/a
7617 RM2	n/a	n/a	7617 RM2	n/a
7617 RM3	n/a	n/a	7617 RM3	n/a

Table 2: Listing of SGT stations and ground network marks

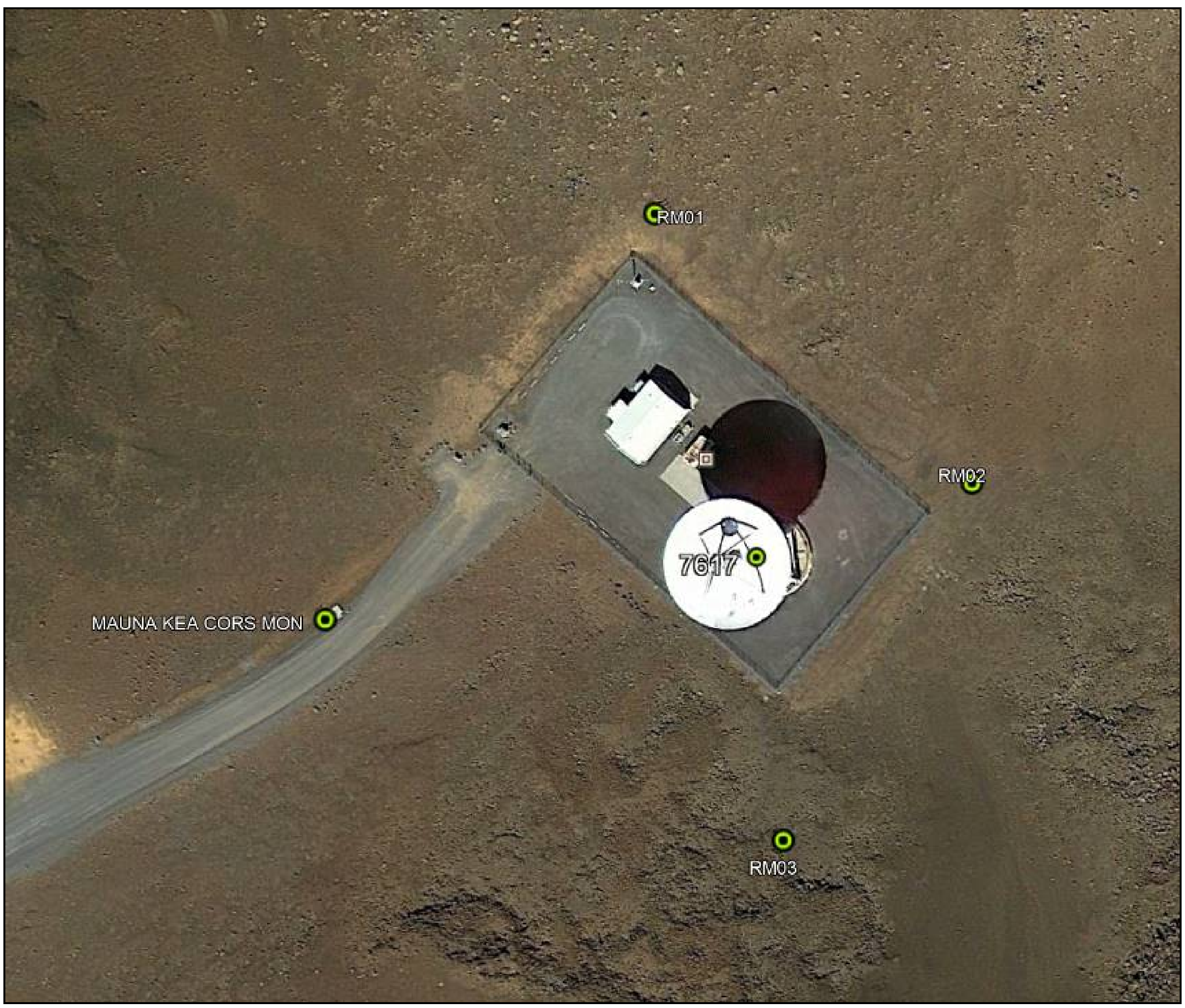
<u>Ground network mark descriptions</u>

7617 RM1 (RM01) is a dimple mark set into and near the top center of a stainless steel rod driven to an unknown depth and enclosed by an access cover stamped 7617 RM1.

7617 RM2 (RM02) is a dimple mark set into and near the top center of a stainless steel rod driven to an unknown depth and enclosed by a an access cover stamped 7617 RM2.

7617 RM3 (RM03) is a dimple mark cast into the top center of a NASA survey disk epoxied into a drill hole in an outcropping of lava stamped 7617 RM 3 JUL 96.

3.1.2 Map of network



Control stations at Mauna Kea VLBA Observatory

3.2 Representation of technique reference points

3.2.1 VLBI

<u>*7617*</u>

The VLBI technique is a radio telescope with a 25-meter dish antenna. The instrument's geometric reference point (GRP), also known as the conventional reference point, invariant point, or system reference point, is an intangible point in space. Observations are referenced to this point, about which the azimuth and elevation axes rotate.

For the VLBI technique, the GRP is a theoretical point at the intersection of the azimuth axis and the line mutually perpendicular to the azimuth and elevation axes. An indirect approach was used to determine the GRP in the survey.

3.2.2 SLR

This space geodetic technique was not represented at the site at the time of survey.

3.2.3 GNSS

<u>*MKEA*</u>

The GNSS technique is an IGS tracking station and NGS CORS. The antenna type at the time of survey was a Javad choke ring antenna (part number 01-570300-01, IGS antenna code JAVRINGANT_DM, serial number 00983). The antenna identifiers matched those in the IGS site log. The GNSS antenna is attached to a steel pillar. The monument is a 4 inch diameter steel pipe cemented 11 feet below ground and protruding 4 feet above ground with a ¾ inch bolt welded to a screw cap on top of the mount.

The GNSS reference point is reported by the International GNSS Service (IGS) to be coincident with the antenna reference point (ARP). The antenna's SCIS radome was removed for survey operations with approval from NASA JPL. An indirect approach was used to determine the GNSS reference point for the survey.

At the time of writing, the IGS site log is available online.
http://www.igs.org/igsnetwork/network_by_site.php?site=mkea00usa

3.2.4 DORIS

This space geodetic technique was not represented at the site at the time of survey.

4 Observations

4.1 Terrestrial survey

The terrestrial survey was completed using an absolute laser tracker system. The instrument measured horizontal angles, vertical angles, and distances to retro-reflector targets which were used to position the marks and techniques.

As part of the observation routine, all angle and distance measurements to ground marks were observed a minimum of three times. Double centering of the instrument was incorporated, measuring in both instrument faces. Meteorological data was observed and atmospheric corrections were applied to all measurements at the time of data collection.

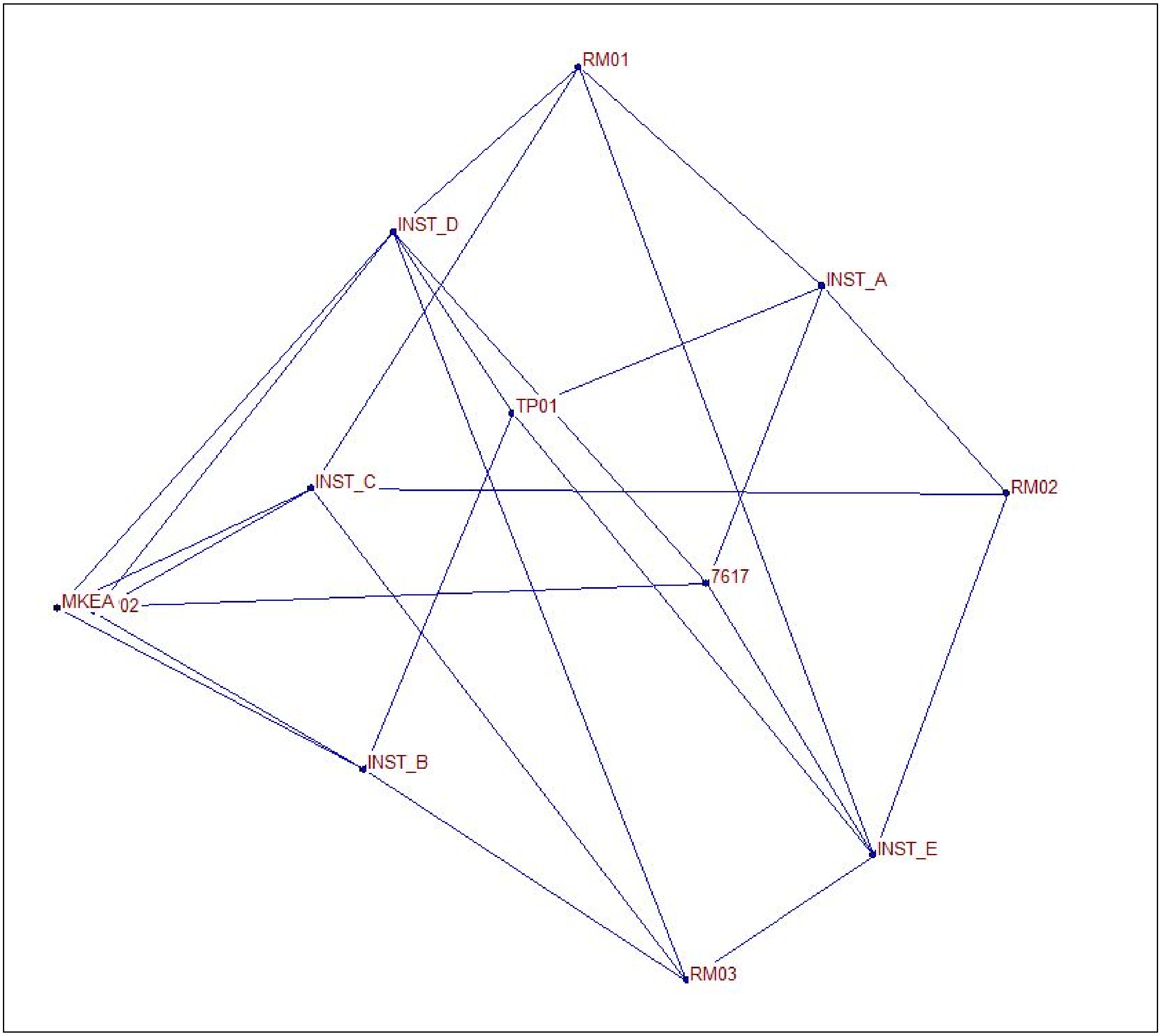
Spatial Analyzer software was used for recording observations and to perform field-level data quality checks for all laser tracker measurements. Star*Net software was used to combine and adjust all observations. A complete list of adjusted observations is available in Star*Net ***.LST*** output file ***MKEA03.lst***.

A diagram of the surveyed network stations is provided.

Vertical offsets of terrestrial observation stations (units in meters)

STATION	STAGE 1	STAGE 2	PRISM	TOTAL OFFSET
7617 RM1	Rod D	MTA D, Bottom Plate	Leica Nest with Prism	
	1.0415	0.0098	0.0550	1.1063
7617 RM2	Rod B	MTA B, Bottom Plate	Leica Nest with Prism	
	1.0427	0.0098	0.0550	1.1075
7617 RM3	Rod E	MTA C, Bottom Plate	Leica Nest with Prism	
	1.0410	0.0098	0.0550	1.1058

Table 3



Terrestrial Network Diagram

4.2 Leveling

No leveling was conducted for this survey.

4.3 GNSS

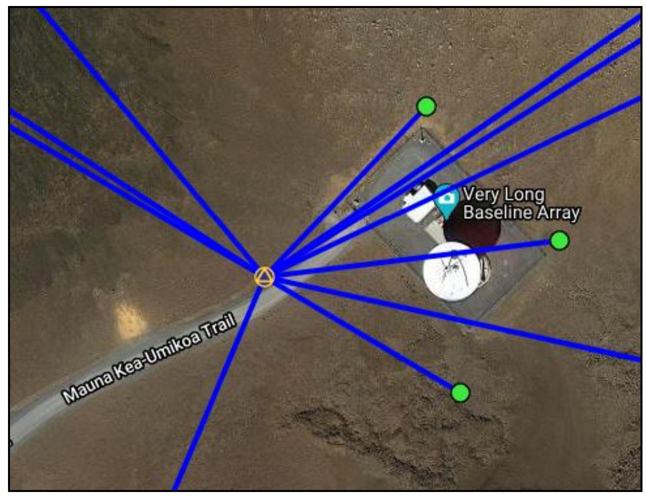
GNSS data was collected to generate 3-dimensional ITRF2014 vectors between stations at the epoch date of survey 2020/01/19. Over multiple days, simultaneous long-session (24+ hour) observations were taken at 7617 RM1, 7617 RM2, and 7617 RM3. Publicly available observation data was also obtained for CORS in the region.

GNSS observations were processed with a minimally constrained, “hub” design emanating from NGS tracking station MKEA. Using the baseline processing engine within NGS’s OPUS Projects software, ITRF2014 vectors to the network stations and CORS were generated via ITRF2014 satellite orbits. The resulting GPS vectors were used in a combined network adjustment to align the terrestrial survey to ITRF2014.

Vertical offsets of GNSS observation stations (units in meters)

STATION	STAGE 1	STAGE 2	TOTAL OFFSET
7617 RM1	Rod D	MTA D, Overall	
offset	1.0415	0.1507	1.1922
7617 RM2	Rod B	MTA B, Overall	
offset	1.0427	0.1507	1.1933
7617 RM3	Rod E	MTA C, Overall	
offset	1.0410	0.1507	1.1917

Table 4



GNSS network diagrams

4.4 General comments

Resection method for terrestrial observations

In the terrestrial survey, the resection principle was employed to measure between network stations indirectly with the laser tracker. The ground marks were occupied with the reflector targets mounted on range poles. The instrument did not occupy the marks directly but was instead setup at arbitrary points between the stations. At each instrument occupation, a series of measurements were taken to the surrounding visible stations. By observing common features from different instrument occupations, the relative positions of both the instrument and targets were established.

The resection procedure was chosen to take advantage of the laser tracker's high-precision capabilities and mitigate setup errors. By setting up at arbitrary points rather than occupying the marks, horizontal and vertical centering errors were statistically insignificant. While the vectors between stations were not observed directly, the measurements were precise enough to determine relative positions with at the sub-millimeter level.

Establishing points via circle-fitting

As noted, determining coordinates of the VLBI geometric reference point (GRP) was achieved using an indirect approach. The "circle-fit" theory is briefly described. A point, as it revolves about an axis, scribes an arc. The arc defines a circle and a plane simultaneously. The axis can then be defined as it 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 parameters to the axis relative to a local coordinate system.

Tracker measurements project coordinates from the local ground network to a target/reflector attached to a geodetic technique instrument as it moves about the instrument's axis, thereby providing the necessary information to locate a single axis. The same procedure must be done for the opposing axis of the instrument in the same local reference frame. The point along the azimuth axis that is orthogonal to the elevation axis is a technique's GRP.

Precise observations involving a single target/reflector secured to the radio telescope, measurements from at least two instrument occupations, and numerous measurement per axis serve to ensure a millimeter level of positional precision is achieved. The VLBI GRP was determined in this manner.

Target/reflector affixed to VLBI antenna for elevation and azimuth rotation sequences

Coordinates for the IGS station MKEA's reference point were also determined using a circle-fitting routine. 3-dimensional measurements were taken to a target/reflector at multiple points along the top of the antenna's choke ring. A sufficient number of points were measured to scribe a circle in place. After accounting for the height of the reflector, the antenna's mechanical offsets, and the IGS reported ARP eccentricity, coordinates were computed to represent the mark MKEA. Measurements were taken from three independent locations for redundancy.

Observations of the choke ring were used to determine the GNSS reference point through circle-fitting

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 circle-fitting, as described above. This allowed for analysis of the VLBI's technique's azimuth axis, elevation axis, axial offset, and GRP. Circle-fitting was also used to determine the GNSS technique's reference point.

Terrestrial observations of the ground network and SGTs were brought from Spatial Analyzer to Star*Net software to be combined with the GNSS observations for rigorous least squares adjustment. The combined geodetic adjustment produced coordinates and variance-covariance information for all surveyed features. Adjustment parameters and results are available in Star*Net output file ***MKEA03.lst***.

5.1.2 Topocentric coordinates and covariance

Axis was used to compile topocentric coordinate estimates from the combined geodetic adjustment. Using the GNSS observations, the terrestrial survey was aligned to the reference frame ITRF2014 (epoch 2020/01/19). Complete covariance information for all network stations are available in AXIS output file ***output.axs***.

Surveyed topocentric coordinates, ITRF2014 (epoch 2019/01/19)						
Station	***E(m)***	***N(m)***	***U(m)***	***SE(m)***	***SN(m)***	***SU(m)***
Space geodetic technique stations						
MKEA	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7617	87.3116	3.2791	8.3509	0.0004	0.0005	0.0004
Ground network marks						
7617 RM1	70.1255	72.8411	-3.6323	0.0004	0.0003	0.0003
7617 RM2	127.6473	15.4117	-8.4882	0.0003	0.0004	0.0004
7617 RM3	84.5712	-50.1110	-4.3923	0.0004	0.0003	0.0004

Table 5

5.1.3 Correlation matrix

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

5.1.4 Reference temperature of radio telescope

The International VLBI Service reports a reference temperature for VLBI SGT 7617 of 0.6 degrees Celsius and a reference pressure of 639.0 hPa. At the time of writing, file ***antenna-info.txt*** was not available online. A 2015 version was used. https://ivscc.gsfc.nasa.gov/program/control_files.html

During survey observations of the radio telescope, the mean temperature was 10.3 degrees Celsius and the mean pressure was 654.7 hPa. The vertical component of the GRP coordinate was not corrected for thermal expansion/retraction of the radio telescope support structure.

5.2 GNSS

5.2.1 Analysis software

NGS's OPUS Projects software was used to process and analyze IGS2014 vectors (considered interchangeable with ITRF2014 vectors) between stations at the epoch date of survey (2020/01/19). The resulting vectors can be found in OPUS Projects output file ***network-final.gfile***.

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 output file ***MKEA03.lst***.

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 ITRF2014 (2020/01/19). Complete covariance information for all network station is available in AXIS output file ***output.axs***.

Surveyed geocentric coordinates, ITRF2014 (epoch 2020/01/19)						
STATION	***X(m)***	***Y(m)***	***Z(m)***	***SX(m)***	***SY(m)***	***SZ(m)***
Space geodetic technique stations						
MKEA	-5464105.4083	-2495165.4375	2148291.6814	0.0000	0.0000	0.0000
7617	-5464075.2770	-2495247.6624	2148297.5956	0.0004	0.0004	0.0005

Ground network marks						
7617 RM1	-5464050.7243	-2495217.5573	2148358.9851	0.0004	0.0004	0.0003
7617 RM2	-5464040.3715	-2495276.0651	2148303.3064	0.0004	0.0003	0.0004
7617 RM3	-5464081.9612	-2495247.7021	2148243.0454	0.0004	0.0003	0.0003

Table 6: Coordinate estimates for network stations

The local tie vector, emanating from MKEA, is provided below using the coordinates determined in this survey.

Surveyed topocentric tie				
STATION	***EAST (m)***	***NORTH (m)***	***UP (m)***	***DIST (m)***
MKEA	0.0000	0.0000	0.0000	0.0000
7617	87.3116	3.2791	8.3509	87.7713
Surveyed geocentric tie				
STATION	***X (m)***	***Y (m)***	***Z (m)***	***DIST (m)***
MKEA	0.0000	0.0000	0.0000	0.0000
7617	30.1313	-82.2249	5.9142	87.7713

Table 7: Local tie vector emanating from MKEA, ITRF2014 (epoch 2020/01/19)

5.3 Additional parameters

VLBI radio telescope axial offset

Spatial Analyzer software was used to compute the offset distance between the radio telescope's azimuth and elevation axes. The axial offset was computed from five independent observations with an average value of 2.1331 ± 0.0024 m.

5.4 Transformations

ITRF2014 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 ITRF2014 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 the ***.SNX*** SINEX file ***NGSMKEA2001GA.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 output file ***MKEA03.lst***.

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

               Iterations                =      4

               Number of Stations        =     17

               Number of Observations    =    422
               Number of Unknowns        =     73
               Number of Redundant Obs   =    349

   Observation    Count    Sum Squares         Error
                             of StdRes         Factor
   Coordinates        3         0.000          0.000
    Directions       84        75.244          1.041
     Distances       84        65.463          0.971
       Zeniths       83        66.202          0.982
    GPS Deltas      168       190.159          1.170

         Total      422       397.068          1.067

         The Chi-Square Test at 5.00% Level Passed
              Lower/Upper Bounds (0.926/1.074)
```

<u>Comparison with IERS computed tie</u>
IRTF2014 (2020/01/19) computed coordinates were obtained from the IERS. A comparison of the surveyed tie vector against the computed tie is provided where available.

IERS geocentric computed coordinates, ITRF2014 (epoch 2020/01/19)				
STATION	***SOL***	***X (m)***	***Y (m)***	***Z (m)***
MKEA	-	-5464105.4083	-2495165.4374	2148291.6815
7617	-	-5464075.2807	-2495247.6654	2148297.5915

Table 8: IERS computed coordinates

Surveyed tie vs. IERS computed tie						
	NGS 2020 geocentric tie discrepancies			**NGS 2020 topocentric tie discrepancies**		
STATION	***DX (mm)***	***DY (mm)***	***DZ (mm)***	***DE (mm)***	***DN (mm)***	***DU (mm)***
MKEA	0.0	0.0	0.0	0.0	0.0	0.0
7617	3.7	2.9	4.2	-1.2	5.5	-2.9

Table 9: Tie discrepancies between surveyed and computed ties (surveyed minus computed)

Comparing against the ITRF2014 computed coordinates, the current survey has a maximum tie discrepancy of 5.5 millimeters in the North component.

5.7 Comparison with previous surveys

A previous survey was carried out at the site by the National Geodetic Survey, with field observations in 2015. As a check on the results of the current survey, Star*Net software was used to align the current survey to the previous survey in the ITRF2008 reference frame. Topocentric tie vector comparisons are provided for the common surveyed stations. Complete coordinate information is available in the included data products.

Surveyed ties vs. Previous survey (NGS 2015) Topocentric tie discrepancies			
STATION	*DE (mm)*	*DN (mm)*	*DU (mm)*
MKEA	0.0	0.0	0.0
7617	0.2	-0.4	0.0
7617_RM1	0.9	-1.4	-0.5
7617_RM2	2.1	-3.9	-0.3
7617_RM3	-1.6	-2.2	-1.8

Table 10: Tie discrepancies between current survey and previous survey (current minus previous)

<u>VLBI radio telescope axial offset</u>

Spatial Analyzer software was used to compute the offset distance between the radio telescope's azimuth and elevation axes. A comparison between the axis offset reported by the National Geodetic Survey, 2015 observations are provided in the following table.

GRP for:	Axis Offset Reported By NGS, 2020 (m)	Axis Offset Reported By NGS, 2015 (m)	Difference(m)
7617	2.1342 ± 0.0003 m	2.1331 ± 0.0024 m	0.0011

Table 11: Comparison of axial offset distance for VLBI antenna 7617, as measured during the current NGS survey, against the offset distance measured during the 2015 NGS survey

6. Planning aspects

Contact Information

The primary contact for information regarding SGT 7617 is NRAO employee Walter Brisken Walter's contract information is:

Walter Brisken
NRAO
Deputy Assistant Director for VLBA Development
(575) 835-7133
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On site contacts:

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6.1 Recommendations

- A 4 wheel drive vehicle is required to drive the last few miles of the only access road leading to the Observatory. The team procured a 4-door Jeep that provided ample room to transport equipment to the site.
- Major shipping companies, at least UPS, do not deliver to the Observatory. Support equipment should be shipped to a "shipping" center in Hilo or Kona and "held for pickup" for the survey team.
- The weather and the sun can be extreme at the Observatory, even in the middle of winter, plan accordingly.
- Mauna Kea is considered a cultural and environmentally sensitive area. The survey team will need to conduct field measurements in a manner having minimal impact on the local environment. If new control marks are required, approval from the office of Mauna Kea, Stephanie Nagata, Director should be contacted well in advance of the survey.
- Office of Maunakea Management (OMKM) requires all visitors to the site performing work must review the Maunakea User Orientation. Specialized Maunakea User Orientation must be completed prior to the survey and is a requirement to access the site. Contact the Office of Maunakea Management for details.

7. References

7.1 Name of person(s) responsible for observations

Kevin Jordan (kevin.jordan@noaa.gov)
John May (john.may@noaa.gov)

National Geodetic Survey
538 Front Street
Norfolk, VA 23510

Phone: (757) 441-5467

7.2 Name of person(s) responsible for analysis

Kevin Jordan (kevin.jordan@noaa.gov)
Benjamin Erickson (Benjamin.Erickson@noaa.gov)

National Geodetic Survey
538 Front Street
Norfolk, VA 23510
Phone: (757) 441-5467

7.3 Location of observation data and results archive

National Geodetic Survey
15351 Office Drive
Woodford, VA 22580
Phone: (540) 373-1243
https://www.ngs.noaa.gov/corbin/iss/

Contact for previous surveys and data:
National Geodetic Survey
Instrumentation & Methodologies Branch
15351 Office Drive
Woodford, VA 22580
Phone: 540-373-1243

7.4 Works referenced

Nothnagel, Axel (2003). Layout of Local Tie Report. Proceedings of the IERS Workshop on site co-location. Matera, Italy, 23–24 October 2003 (IERS Technical Note No. 33).
https://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn33.html

Poyard, Jean-Claude et al. (2017). IGN best practice for surveying instrument reference points at ITRF co-location sites (IERS Technical Note No. 39).
https://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn39.html

National Geodetic Survey 2015 Mauna Kea Local Tie Information Report.
https://www.ngs.noaa.gov/corbin/iss/data/MKEA/MKEA2015DataProducts.zip

International GNSS Service. http://www.igs.org/

International VLBI Service. https://ivscc.gsfc.nasa.gov/