Calculating optical observation residuals from GPS satellites

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ABSTRACT

Understanding the measurement errors for a sensor is crucial when using the measurements in a precision application. Expected measurement error informs how data from multiple sensors can be used together. It is possible to compensate for consistent biases in the data. An up-to-date history of measurement error can also yield insights into the sensor's health and operations.

Calibrating and understanding a sensor's measurement error requires knowledge of the observed target's true location over some time period. This information is rarely self-reported by satellites with users typically relying on satellite laser ranging for the necessary data. However, "Position, Navigation, Timing" (PNT) satellites, such as the GPS constellation, constantly broadcast their location in the form of a navigation message that we have found can be used to calculate their exact position and velocity over a specified time period.

This paper describes a method to use navigation messages archived by NASA Crustal Dynamics Data Information System (CDDIS) from GPS satellites to compute the residuals of metric observations collected on satellites by a ground-based optical sensor. The method of calculating residuals is described with the objective to lower the barrier to entry, both in accessing the required data and assembling the required algorithms. The goal is to promote wider use of this or equivalent methods.

This paper presents several sets of residuals produced using this method from observations collected by the MITRE Telescope Network. This method can also be adapted to compute residuals using satellites from other GNSS/PNT constellations other than GPS whose navigation messages are also hosted on CDDIS.

1. INTRODUCTION

Over the past decade, the MITRE Telescope Network (MTN) has grown from a single sensor located at the United States Air Force Academy in Colorado Springs to a number of sensors which are owned and operated by or receive substantial technical support from MITRE. MTN sensors, being research and development platforms, are each unique in the hardware and software they use, and their configuration can change over time as project focus and research needs evolve. While each of these heterogeneous sensors is operated to suit the needs of the supporting projects, in order to bring the MTN to bear as a cohesive resource, some measure of the collected data quality was needed – specifically the satellite location measurement error, i.e., "observation residuals".

As the MTN was developed, the tools to calculate this "measurement error" were built but were sparsely documented and not consistently adopted. This paper documents the described process, for reference, for critique and refinement, and to promote a habit of data quality monitoring among the MTN community.

We also note that this method has applicability outside the MTN. To the extent it is adopted, this approach could promote a common understanding of measurement errors for improved data sharing. Further, the method presented is meant as a supplement or alternative to other calibration methods, such as using satellite laser ranging data, not as a replacement.

2. HIGH ACCURACY EPHEMERIS FROM CDDIS

NASA's Crustal Dynamics Data Information System (CDDIS) was started in 1982 as a data repository to support the Crustal Dynamics Project (CDP). CDP was started in the 1970's to study the Earth's shape and the movement of the Earth's crust. CDDIS supports a variety of message types that are broadcast from several PNT satellite constellations and received at numerous sites around the world. These sites, collectively referred to as "Global Navigation Satellite Systems" (GNSS), include the navigation message type broadcast by GPS, Galileo, GLONASS, QZSS, BeiDou, SBAS, and IRNSS constellations. These navigation messages provide highly accurate individual satellite positions that we have found can be used to precisely calculate the residuals of space track observations.

2.1 DOWNLOADING NAVIGATION DATA

Anonymous access to the GNSS data was discontinued after October 31, 2020, however CDDIS still allows access, free of charge, with an *Earthdata* login. While CDDIS hosts many different types of data, the following explanation focuses solely on the data required to compute observation residuals. [1]

GNSS navigation files are available daily – several hours after the end of the UTC day. These files can be found at *https://cddis.nasa.gov/archive/gnss/data/daily/yyyy/brdc/*, substituting "yyyy" for the desired year. "BRDC" [Broadcast Ephemerides] station code is the daily broadcast ephemeris file. This file combines messages from multiple receivers into a single non-redundant file. File type "R" meaning "From Receiver data using vendor or other software", is used with this process. The MN data type includes navigation messages from all GNSS constellations [2]. An example file for January 1, 2022, is available here:
https://cddis.nasa.gov/archive/gnss/data/daily/2022/brdc/BRDC00IGS_R_20220010000_01D_MN.rnx.gz

These GNSS navigation files are formatted in the Receiver Independent Exchange Format (RINEX) file format. This format is standardized and is described in the following section.

Once retrieved, the contents of the navigation messages can then be ingested by a designated algorithm to calculate the given satellite's ephemeris over a defined period. This algorithm is uniquely implemented by each constellation and documented in an Interface Specification document or equivalent. For GPS, this algorithm is defined in the IS-GPS-200 document [3].

2.2 INTERPRETING RINEX FILE TYPE

The RINEX format was created to hold GPS data for geodesy studies. RINEX version 3 includes the navigation message type. For a complete description of the RINEX file formats and how to interpret their contents, refer to document "RINEX The Receiver Independent Exchange Format Version 3.04". [4]

2.2.1 MAPPING NAVIGATION MESSAGES TO THEIR RESPECTIVE SATELLITE IDS

The GNSS navigation messages in the RINEX files are distinguished from each other through an identifying code at the start of each message. This is represented as a single letter followed by a 2-digit number; for GPS navigation messages, these codes are in the form of "GXX", where "G" signifies that the following navigation message data is for a satellite in the GPS constellation, and the "XX" is the corresponding Pseudo-Random Noise (PRN) code. Fig. 1 below shows an example navigation message.

```
G01 2021 10 15 00 00 00 5.391854792833E-04-1.080024958355E-11 0.000000000000E+00
     3.600000000000E+01 4.628125000000E+01 3.907662769839E-09 2.866804233652E+00
     2.263113856316E-06 1.106586505193E-02 4.014000296593E-06 5.153675823212E+03
     4.320000000000E+05-3.539025783539E-08 3.406555823124E-01-9.872019290924E-08
     9.859876504576E-01 3.133750000000E+02 8.899280401378E-01-7.863184676061E-09
     2.300095808223E-10 1.000000000000E+00 2.179000000000E+03 0.000000000000E+00
     2.000000000000E+00 0.000000000000E+00 5.122274160385E-09 3.600000000000E+01
     4.248670000000E+05 4.000000000000E+00 0.000000000000E+00 0.000000000000E+00
```

Fig. 1. Example navigation message from GPS PRN 01, for October 15, 2021

These identifying codes are not immediately useful for calculating observation residuals for sensors that tag their observations to a given satellite's NORAD ID, or its international designator. Before any residuals can be computed, one must also know, or have a database at hand to reference, the mapping between these identifying codes and the corresponding satellite ID. Furthermore, PRN codes for a given GNSS satellite can change over time, meaning that this mapping is also time dependent.

These mappings are maintained by each of the constellation's organizations, often mapping the PRN code to a Space Vehicle Number (SVN). Space Vehicle Numbers, unlike PRN codes, uniquely identify physical satellites and therefore have a fixed mapping to identifiers such as a satellite's NORAD ID or international designator.
A convenient source for mapping PRN codes to satellite IDs is currently maintained by the International GNSS Service (IGS) as Satellite Metadata files [5]. These files contain a wide range of data that includes an archive of PRN-to-SVN maps over time, and mapping between SVN to both NORAD IDs and international designators.

2.2.2 TIME SYSTEMS OF GNSS CONSTELLATIONS

Each satellite within the GNSS employs a unique time coordinate system. It is important to maintain the association between each time measurement and its corresponding reference system. The time tag of a navigation message provided in the RINEX files is given in the respective satellite's time system, which includes the Time of Ephemeris parameter that is needed to calculate the satellite's state vector over time. The algorithm to calculate a satellite's position and velocity vectors requires the input time to be in the satellite's given time system. If a different time system is desired, for example UTC, then a conversion process is needed to convert the navigation message time stamp from the satellite's time system to the desired time system.

The GPS time system and UTC run parallel to each other with a sub-microsecond difference. However, the offset between GPS time and UTC is not constant and can change over time, such as whenever a leap second is introduced by the International Earth Rotation and Reference Systems Service (IERS). The GPS time system is on a continuous scale, whereas UTC is periodically adjusted to keep it aligned to solar time (UT1) to within 1 second [6]. As such, the offset between GPS and UTC will be an integer number of seconds that is provided in the header section of the RINEX header[1]. To convert GPS time to UTC, subtract the number of seconds defined by that parameter from the given time stamp.

Time systems of other GNSS constellations follow the same rules. SBAS, QZSS, Galileo, and IRNSS have time systems that are nearly identical to GPS time. The GLONASS time systems runs on UTC (more precisely, UTC(SU)), and BeiDou's time system is defined to be 14 seconds behind GPS time. There are small differences (modulo 1 second) between the time systems that may need to be accounted for, depending on the level of accuracy needed in the end solution. The RINEX file's header will contain the information needed to precisely convert a given constellation's time system to UTC through the "TIME SYSTEM CORR" parameters.

2.2.3 GNSS BROADCAST NAVIGATION ALGORITHMS

The algorithms to calculate GNSS satellite ephemeris are given in interface specification documents. For GPS, this document is named IS-GPS-200 [3], which is on revision M as of May 21, 2021.

The parameters needed to execute the algorithm are provided in the navigation message. Constants such as the Earth's standard gravitational parameter μ and rotation rate Ω ̇_E will be given in the interface specification document for the given GNSS constellation. The input time for the equations is required to be defined in the given satellite's time system, and as such the output ephemeris will be timestamped to that satellite's time system. If a different time system is desired (e.g., UTC), then the timestamps will need to be converted separately, after the position and velocity vectors have been calculated.

The output of these equations is the position vector of the satellite at the desired time (defined in the given GNSS's time system) in an Earth-fixed coordinate system. The exact Earth-fixed coordinate system will be defined in the

[1] The RINEX file lists this parameter as "LEAP SECONDS", however the concept of a leap second is traditionally defined to be between UTC and International Atomic Time, or TAI. [11] The difference between the GPS time system and TAI is constant at 19 seconds, so the value of the LEAP SECONDS parameter in the RINEX header is actually the difference between traditional leap seconds (TAI – UTC) and the GPS/TAI offset (TAI – GPS), i.e. RINEX "LEAP SECONDS" = (TAI – UTC) – (TAI – GPS) = GPS – UTC, or GPS = UTC + "LEAP SECONDS"

GNSS's Interface Specification document. For GPS, the user broadcast equations will provide the position of the satellite's antenna phase center [3] in the WGS-84 Earth-centered, Earth-fixed (ECEF) coordinate system. The offset between the satellite's antenna phase center and its center of mass is typically on the order of a meter or less. Depending on the level of accuracy desired, one can add the additional step to convert the state vector relative to the satellite's center of mass. The IGS website is again a useful source for satellite antenna phase center offsets.

The GLONASS and SBAS constellations broadcast navigation files that differ from the other GNSS constellations (i.e., GPS, Galileo, BeiDou, QZSS, and IRNSS). The contents of these messages instead provide the position and velocity state vectors directly. The user can calculate the satellite's position and velocity at a given time by interpolating, or extrapolating, the state vectors in the messages to the desired time. Keep in mind that the times provided in GLONASS and SBAS messages are based on their respective constellation's satellite system time.

For SBAS and GLONASS, the provided state vectors are defined in the ECEF coordinate frame [7] and the PZ-90.02 ECEF coordinate frame [8], respectively.

3. RESIDUAL COMPUTATION

Both the reported satellite position, as decoded from a GNSS navigation message, and the observed satellite position must be converted to a common reference frame for comparison. Focusing on optical observations, there are four steps required to calculate residuals which are outlined here. Two of those steps, mentioned below, are the application of corrections that need to be applied to the observations before comparison with reported satellite position. The user should consult with the source of the observations to verify the applicability of these steps and corrections to the associated data.

3.1 STELLAR ABERRATION CORRECTION

Stellar aberration is the apparent shift in a star's position due to the motion of the Earth. For an explanation of stellar aberration, see the U.S. Naval Academy paper [9]. In order to correct for stellar aberration, the time of the observation, and location – and motion – of the sensor is required. This information is typically available to the sensor when the observation is created, therefore this correction is sometimes applied to the observation at the sensor itself. This correction is required if the observation is created using the position of the satellite relative to the position of stars in the captured image; if the observation is created using a measure of where the sensor was pointing, for example by using a mount model, then this correction does not apply.

The target satellite and the Earth are also moving relative to each other; however, the effects of the resulting aberration are ignored here.

3.2 CONVERSION TO TEME

To properly calculate observation residuals, it is also important to know in which Earth-centered Inertial (ECI) coordinate frame a set of sensor observations are defined. Right Ascension and Declination (RADEC) observations from sensors may be generated in the J2000 ECI frame, which may differ from the ECI coordinate frame used for the truth ephemeris data. When calculating observation residuals, a common frame must be established, and all relevant data be converted to this frame using the proper coordinate transformation methods.

The True Equator, Mean Equinox (TEME) frame can be used as a common coordinate frame for the sensor observations and truth ephemeris. In this case, TEME of Date is assumed. A description of the TEME frame, and how it differs from the J2000 ECI frame, can be found in Vallado [10]. One advantage of the TEME frame is that some sources of reference ephemerides, such as those generated from the Astrodynamics Support Workstation, an operational system used for, among other missions, conjunction assessment [11], are already defined in the TEME frame. Ephemerides generated by propagating satellite ELSETs using SGP4 are also defined in the TEME coordinate frame by default.

There are many sources available for properly transforming between various ECI and ECEF coordinate frames (note: the ECEF coordinate frame is also known as ECF or ECR). One set of widely available methods has been developed by David Vallado [10] in several programming languages including C++ and MATLAB.

The process described in this paper converts, if necessary, sensor RADEC observations in the J2000 ECI frame into RADEC observations in the TEME ECI frame. Correspondingly, the truth ephemeris used for comparison must also be converted, if necessary, to the TEME ECI frame and subsequently transformed into right ascension and declination values.

3.3 LIGHT-TIME CORRECTION

When the image of the satellite is received by the sensor it has already been delayed by the travel time of the light. Generally, optical sensors do not measure range, but the truth ephemeris can be used to calculate the range and, using the range, the time that the satellite was in the observed position can be computed.

The truth ephemeris, at the reported time of the observation, is converted from ECI to ECR, if necessary. ECR truth ephemeris is then converted to RAE. The corrected time of observation is computed by adjusting the reported time backwards, based on the range of the satellite from the sensor according to the truth ephemeris, to match the time when the light left the satellite.

3.4 FINDING ANGLE ERRORS

Ephemeris at the corrected time of the observation is converted to both ECI and ECR. The ECR ephemeris is used to recompute RAE. The ECI ephemeris is used to compute right ascension and declination in TEME.

The right ascension and declination of the ephemeris is subtracted from the right ascension and declination of the observation, respectively. The difference in right ascension is scaled by the cosine of the observed declination to account for the singularity of right ascension at a declination of +/-90 degrees. The scaled difference between the observed right ascension and the truth ephemeris, and the difference between observed declination and the declination of the truth ephemeris constitute the residual in right ascension and declination, respectively.

4. TESTING AND VALIDATION

In this section a navigation message is decoded, and the resulting positions are compared to the SP ephemeris of the satellite from *space-track.org*. Next, the observation residuals are computed for a number of observations from the MITRE Telescope Network and several anomalies are discussed.

4.1 GENERATING EPHEMERIDES FROM GPS NAVIGATION MESSAGES

For SATID (NORAD ID) 24876, there are 12 messages present in the RINEX file, spaced every 2 hours from 0200 UTC until 2200 UTC. The first published navigation message in the RINEX file is given below in Fig. *2*.

```
G13 2021 09 10 02 00 00 1.833131536841E-04 5.343281372916E-12 0.000000000000E+00
     8.000000000000E+00-6.231250000000E+01 4.320894268304E-09-1.922018069002E+00
    -3.328546881676E-06 5.403212970123E-03 1.053512096405E-05 5.153684898376E+03
     4.392000000000E+05 8.568167686462E-08-3.100266999685E+00-1.154839992523E-07
     9.687677178183E-01 1.777187500000E+02 9.614575439716E-01-7.868899199808E-09
    -3.417999516257E-10 1.000000000000E+00 2.174000000000E+03 0.000000000000E+00
     2.000000000000E+00 0.000000000000E+00-1.117587089539E-08 8.000000000000E+00
     4.320180000000E+05 4.000000000000E+00
```

Fig. 2. Sample RINEX message

The position state vectors generated from these navigation messages were compared with the corresponding SP (Special Perturbations) ephemeris from *space-track.org*. When comparing the navigation message generated state vectors with the SP ephemeris, the nearest navigation message in time was used and small discontinuities were observed in the transition from one navigation message to the next. A quantitative comparison between the navigation message state vectors and SP ephemeris is withheld here pending release permission from *space-track.org*. Suffice to say, the navigation message state vectors matched the SP ephemeris close enough to be used in the process of calculating observation residuals.

4.2 CALCULATING RESIDUALS ON SENSOR OBSERVATIONS

The MITRE Tokyo Telescope (MTT) is a mobile telescope system based in central Tokyo, Japan. Residuals were computed on observations of several GPS satellites collected by the MTT over several nights between April 7, 2021, and April 19, 2021. Observations from the MTT are expressed in J2000 Right Ascension/Declination, need to have light-time correction applied, and need to have aberration correction applied. A summary of the observations and resulting residuals, displayed as arithmetic mean and standard deviation (STD), is show in Table 1, and graphically in Fig. 3.

Table 1. Select MTT Observations with Summary of Residuals

SATID	**DOY**	**Number of Observations**	**RA (deg)**		**Dec (deg)**	
			Mean	**STD**	**Mean**	**STD**
28190	097	15	5.56	1.67	-3.37	2.59
	109	24	5.04	2.25	-5.02	2.58
28874	098	6	-6.05	1.75	4.97	2.86
39741	097	15	-5.02	2.10	4.75	2.04
40105	108	25	-5.56	3.37	4.75	2.66
43873	109	7	13.13	46.01	7.58	5.82

Several observations can be made, subject to the small sample size. First, the observations fall into two distinct groups: the first group has a positive RA bias of about 5 arcseconds and a negative DEC bias of about 4 arcseconds, and the second group is opposite, with a negative RA bias and a positive DEC bias. Second, if these biases could be removed, the observations would be roughly within +/- 5 arcseconds; MTT has a theoretical angular resolution of approximately 2.5 arcsecond so the magnitude of these residuals, while large, is not unsurprising. Finally, one of the observation sets contain bad data which will be discussed shortly.

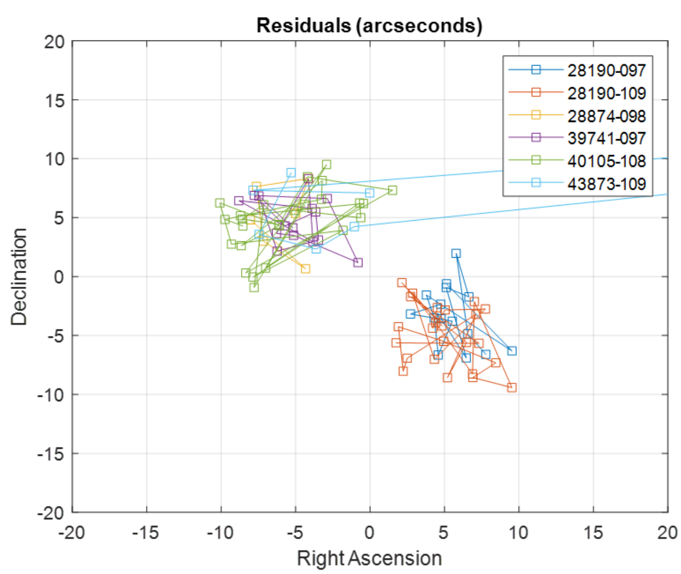

Fig. 3. Residuals of select MTT observations

As seen in Fig. 4, the two groupings of residuals are clearly delineated by measurement azimuth. Based on this, there appears to be a feature in the MTT processing or operations which cause observations east of approximately azimuth 180 to have one set of biases and observations west of approximately azimuth 180 to have a different set of biases. Having discovered this feature of the residuals, the cause can be diagnosed and rectified. In the meantime, to the extent that this feature holds for all observations and measurement geometries, the biases are predictable and can be removed as a form of post-processing.

Collecting a rich set of calibration data, over time and many collection geometries, allows for this type of post-processing to be performed with high confidence.

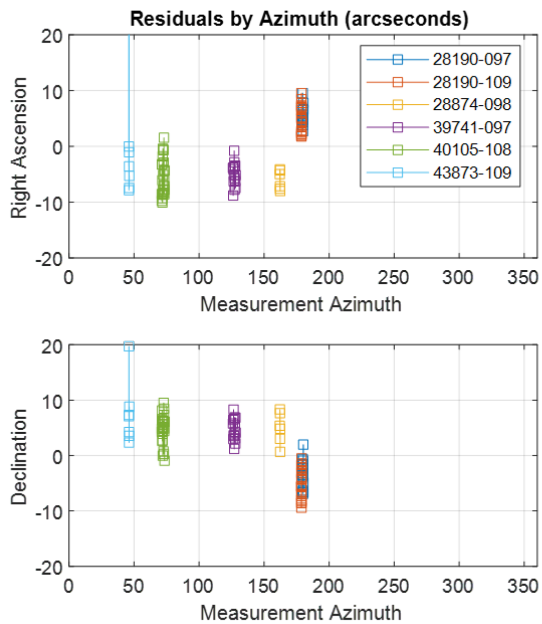

Fig. 4. Residuals of select MTT observations by measurement azimuth

4.3 EXAMPLE RESIDUAL CALCULATION

Table 2 shows the step-by-step process leading to a measurement residual being calculated for an observation from the MTT on satellite 28190 taken on day 97 of 2021. The table provides key inputs and products from the nine steps, starting with the original observation measurement (STime , Right Ascension, and Declination) and ending with the Right Ascension and Declination error in arcseconds.

First, for step 1, aberration correction is applied to the measurement using the original time, Right Ascension and Declination measurements, along with the location of the sensor. Next, for step 2, the measurement is transformed from J2000 to TEME.

In step 3, the satellite's location is calculated using the navigation message and the time of the measurement. Using the location of the sensor in step 4, a range from the sensor to the satellite is computed in order to calculate the light-time delay. The measurement time is adjusted to correspond to the time in which the satellite was in its observed location which was slightly before the time that the measurement was relocated. In step 5, the location of the satellite is recomputed using the corrected time.

In step 6, the location of the satellite is transformed to Right Ascension and Declination. Step 7 finds the difference between the satellite's position in Right Ascension and Declination and the observed position – the observation residual. Step 8 scales the residual of the Right Ascension measurement by the cosine of the measured Declination. And finally, step 9 shows the residual as expressed in arcseconds.

Table 2. Example calculations for observation of satellite 28190

		STime	**RA J2000 (deg)**	**Dec J2000 (deg)**			
	Original Measurement	121097.52088	162.882563	4.842619			
		STime	**RA J2000 (deg)**	**Dec J2000 (deg)**	**Sensor Lat/Lon/Alt (deg/deg/m)**		
1	**Aberration Correction**	121097.52088	162.886787	4.840721	35.661381	139.724945	22
		STime	**RA TEME of Date (deg)**	**Dec TEME of Date (deg)**			
2	**Observation RA/Dec TEME**	121097.52088	163.162174	4.729512			
		STime	**Best Nav Timestamp**	**Nav ECR (m)**			
3	**Nav Sat Location**	121097.52088	121097.499792	-19729801.6	16757530.	5410634.0	
		Range to Nav (m)	**Light-Time Correction**	**Corrected STime**			
4	**Light-Time Correction**	20768650.9	0.069277	121097.520879			
		STime	**Best Nav Timestamp**	**Nav ECR (m)**			
5	**Nav Sat Location**	121097.52087	121097.499792	-19729750.9	16757516.	5410850.7	
		STime	**RA TEME of Date (deg)**	**Dec TEME of Date (deg)**			
6	**Nav Sat RA/Dec TEME**	121097.52087	163.160007	4.731346			
		RA Residual	**Dec Residual**				
7	**Residuals**	0.002167	-0.001834				
8	**Residuals Normalized by Declination**	0.002160	-0.001834				
9	**Residuals in Arcseconds**	7.77	-6.60				

4.4 OBSERVATIONS OF 43873, DOY 109

As previously noted, and shown in Fig. 5, the residuals for satellite 43873 collected by MTT on DOY 109 contain one outlier. Analysis should always be performed on this type of residual data before accepting biases in order to avoid allowing outlier data to impact future measurement calibration.

Fig. 6 shows the X and Y pixel position in the images for each observation of satellite 43873. An outlier in the X and Y pixel position can be seen which corresponds to the outlier in Right Ascension and Declination measurements.

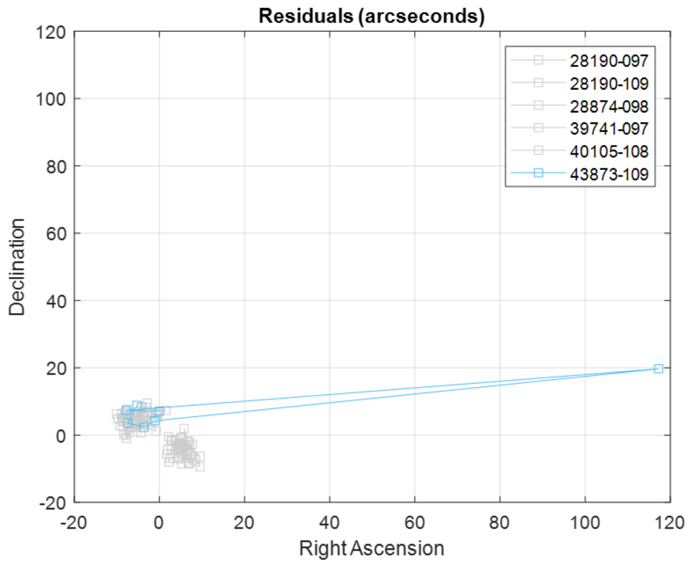

Fig. 5. Satellite 43873 observation residuals with outlier

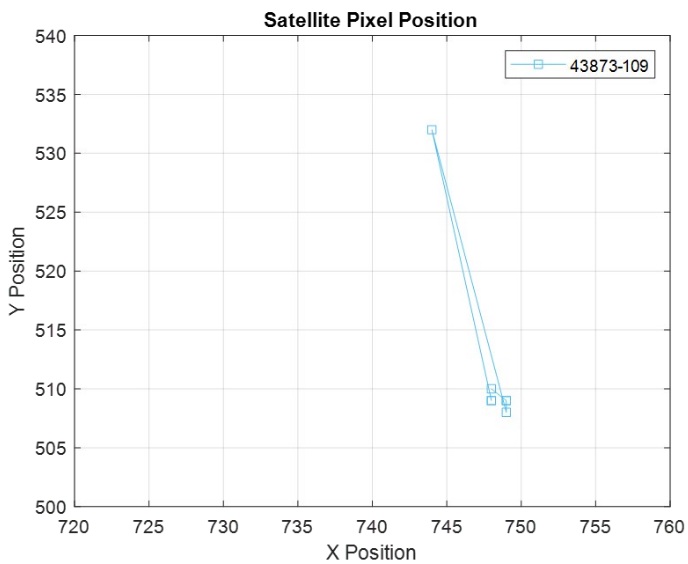

Fig. 6. Satellite 43873 observation X, Y position in image

The image responsible for the outlier data is shown in Fig. 7. Bright ground clutter can be seen on the bottom left and across the image from the lower left to center right, and the stars are obscured in the lower right. Debris on the telescope lenses are also visible. The measured satellite position is circled in purple and labeled with the satellite ID. In this case, the actual satellite can be seen just above the purple annotation – the image processing was likely fooled by the ground clutter.

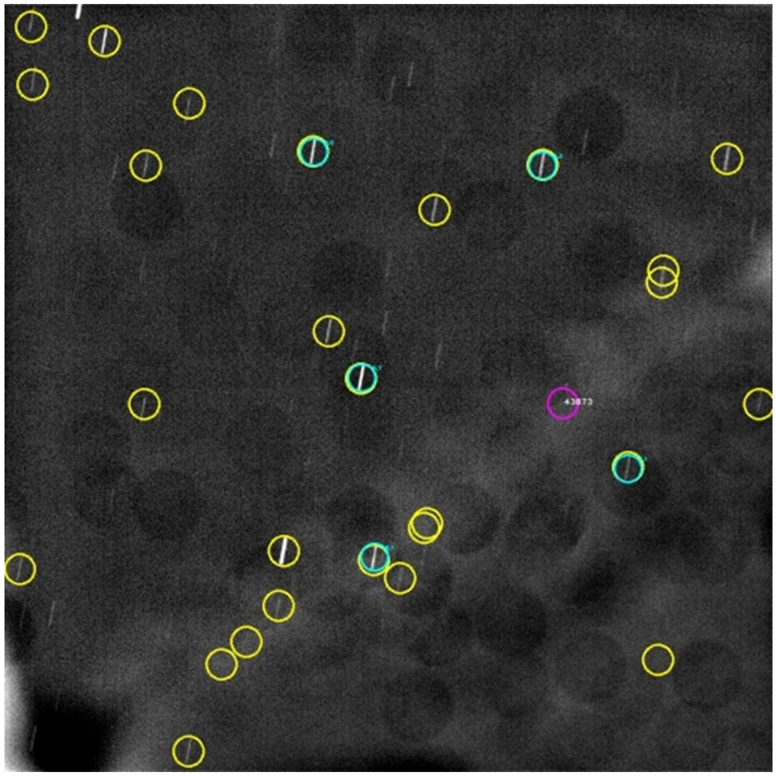

Fig. 7. Image responsible for outlier measurement on satellite 43873

5. CONCLUSION

In this paper, a method is outlined for calculating residuals from optical observations on GPS satellites. The method relies on obtaining high accuracy ephemeris using the Navigation messages archived by CDDIS. For GPS, the document IS-GPS-200 describes how to calculate the ephemeris from the Navigation messages.

Using this high accuracy ephemeris, a process is presented for calculating residuals on GPS observations. Several data corrections are described; this process should be tailored to fit the specifics of the user's data.

Finally, observation residuals were computed on a small set of observations from the MITRE Tokyo Telescope. A pattern in the bias of the residuals was found which could suggest an error in the creation of the observations. An outlying residual was examined and determined to be caused by ground clutter in the originating image.

This process, or an analogous approach, can easily be adopted by space track sensors and performed regularly in order to monitor the health and quality of the sensor, and to communicate the expected errors and biases of the data to the data consumers. The process presented here requires an *Earthdata* login to access the GPS Navigation message data, and the implementation of the associated Navigation equations and required coordinate conversions; these requirements are universally accessible.

Finally, several avenues of follow-on research are possible.

5.1 FUTURE WORK: ADDITIONAL CALIBRATION DATA SOURCES

Although this paper focused on using the GPS constellation, CDDIS also hosts data from satellites in the Galileo, GLONASS, QZSS, BeiDou, SBAS, and IRNSS constellations. A robust residual processing system would handle observations from the satellites in any of these constellations. Not only would this afford more collection opportunities for the sensor but diversifying the source of calibration data should improve the resiliency of the process. Care should be taken when adding additional constellations as the contents of their Navigation messages or the particulars of their navigation algorithm can vary from constellation to constellation.

5.2 FUTURE WORK: REDUCING PROCESS LATENCY

The process presented here depends on downloading daily GNSS navigation files. Although highly convenient for the batch processing of historic data, this process endangers hours or days' worth of observations if an improperly calibrated sensor is not immediately corrected. CDDIS provides Navigation messages on an hourly basis which could be a significant improvement in latency over using the daily GNSS navigation files. Or, in the limit, the user could receive and decode navigation data from the satellites themselves. Ultimately, if steps such as obtaining the Navigations messages as soon as possible and automating this residual calculation process can get the sensor operator residual data with minimal latency it will give the operator the most confidence in the data being collected or the most opportunity to correct any sensor calibration issues.

6. ACKNOWLEDGMENTS

This report captures a portion of the work that Tim McLaughlin pioneered for the MITRE Telescope Network. Tim is known for his tenacious innovation and generosity in sharing tools and solutions. The authors owe Tim a debt of gratitude for the progress he made and the example he set, both on this subject and many others.

7. REFERENCES

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