NRTK observations and their uncertainties in a modern datum

Addressing national datum modernisation, this paper presents a new approach to include static Network Real-Time Kinematic (NRTK) observations and their uncertainties in the survey control network of New South Wales (NSW), Australia.

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The Geocentric Datum of Australia 2020 (GDA2020) is Australia's new national datum. It is defined in the International Terrestrial Reference Frame 2014 (ITRF2014; Altamimi et al., 2016) at epoch 2020.0 and based on a single, nationwide least squares network adjustment that rigorously propagates uncertainty (ICSM, 2021).

DCS Spatial Services, a unit of the NSW Department of Customer Service (DCS), is responsible for the maintenance and improvement of the state's survey control network, which comprises more than 250,000 survey marks on public record made available via the Survey Control Information Management System (SCIMS).

The backbone of the NSW survey control network is provided by CORSnet-NSW, Australia's largest state-owned and operated Global Navigation Satellite System (GNSS) Continuously Operating Reference Station (CORS) network. CORSnet-NSW currently consists of 202 stations, providing fundamental positioning infrastructure that is authoritative, accurate, reliable and easy-to-use for a wide range of applications (e.g. Janssen et al., 2016; DCS Spatial Services, 2022).

This paper describes the growing GDA2020 state adjustment and presents a new approach to include Network Real-Time Kinematic (NRTK) observations and their Positional Uncertainty (PU) in the NSW survey control network. We exploit the automatically computed GNSS baselines between NRTK observations and their Virtual Reference Station (VRS; Landau et al., 2002) to create a connected network that can be adjusted like a static GNSS network. Using a typical urban NRTK survey in Sydney as an example, it is shown that this method offers a rigorous computation of PU while maintaining the quick and easy nature of NRTK positioning.

GDA2020 state adjustment in NSW

Currently, the growing GDA2020 state adjustment consists of approximately 946,000 measurements between 127,000 stations, translating into about 109,000 SCIMS marks and making it the largest Jurisdictional Data Archive (JDA) in Australia. It was computed with DynAdjust using a phased-adjustment least squares methodology that provides rigorous uncertainty across the entire network (Fraser et al., 2022). The GDA2020 state adjustment includes about 114,000 GNSS baselines, 19,600 baselines originating from AUSPOS sessions, 217,000 directions and 225,000 distances. AUSPOS is Geoscience Australia's free online Global Positioning System (GPS) processing service (GA, 2022; Janssen and McElroy, 2022).

However, this only represents 43% of the 250,000 survey marks on public record in NSW, with the remaining 57% having been transformed from the now superseded GDA94 to GDA2020. Uncertainties of these transformed GDA2020 coordinates cannot be computed until the underlying measurements are sourced and readjusted with a well-defined connection to datum in the GDA2020 state adjustment. Presently, DCS Spatial Services is accelerating the process of including additional survey marks in the state adjustment to improve user access to GDA2020 coordinates and uncertainties.

To achieve this, DCS Spatial Services has developed and implemented several innovative, highly automated tools and workflows to prepare, process and ingest existing and new GNSS baseline data, AUSPOS datasets and street-corner traversing data. Over several years, efforts have been undertaken to source, harvest, clean and utilise legacy geodetic measurements (Haasdyk and Watson, 2013), build state-of-the-art GNSS CORS network infrastructure (CORSnet-NSW), observe new high-quality GNSS measurements to connect the existing survey network to CORS (Gowans and Grinter, 2013), and systematically rationalise, maintain, upgrade and collect AUSPOS datasets at key sites across the NSW survey control network, including trigonometrical (trig) stations and Australian Height Datum (AHD) spirit-levelled marks (Gowans et al., 2015; Janssen and McElroy, 2021).

Key components of these datum modernisation efforts have been the preservation and upgrade of survey infrastructure, including physical maintenance of permanent survey marks, and the update of metadata such as survey mark information in SCIMS and survey mark photographs. This will allow future users to achieve DCS Spatial Services' vision of a PU of 20 mm in the horizontal and 50 mm in the vertical (ellipsoidal height) component anywhere in the state and to easily apply transformation tools to move between current, future and various historical datums and local working surfaces.

It is worth noting that a single, state-wide levelling adjustment for NSW is currently also being generated, based on data-mining existing levelling files in the DCS Spatial Services archive and the recently digitised historical levelling data that was used to define the AHD across the state. Presently, the NSW levelling adjustment comprises about 132,000 measurements and 98,000 stations. While still underway, the enormity of this task and its benefits to the profession should not be underestimated. Victoria has already completed a state-wide levelling adjustment, and other Australian jurisdictions are now also starting similar projects.

Determining PU for NRTK observations

Positional Uncertainty (PU) is defined as the uncertainty of the horizontal and/or vertical coordinates of a point, at the 95% confidence level, with respect to the defined datum (ICSM, 2020). It can be separated into Horizontal PU (HPU) for horizontal position and Vertical PU (VPU) for ellipsoidal height. HPU is expressed as the radius of a 95% circle of uncertainty, generally calculated from the standard error ellipse produced by a least squares network adjustment. VPU is a linear quantity and obtained by scaling the standard deviation by 1.96 to convert it to 95% confidence.

Given that NRTK observations are generally treated as point-based position solutions lacking connection to the surrounding datum, it is necessary to investigate how to propagate PU to NRTK observations and assign realistic uncertainties that can be incorporated into the GDA2020 state and national adjustments. When using CORSnet-NSW, single-base RTK positioning results can be expressed as a baseline to the CORS used and thus ingested. However, while NRTK has been shown to provide superior positioning quality compared to single-base RTK and is therefore preferable (e.g. Janssen and Haasdyk, 2011), this process is not as straightforward.

As outlined in Bernstein and Janssen (2021), we initially investigated the possibility of empirically estimating PU based on a dataset of more than 1,500 observations on more than 750 marks, collected under typical conditions encountered in surveying practice. This resulted in estimates of 0.036 m for HPU and 0.059 m for VPU. This simplistic method can be easily applied to all NRTK observations, including historical NRTK data. However, major limitations are that it provides estimated (rather than rigorously calculated) uncertainties and continues to treat NRTK observations as point-based position solutions, therefore exhibiting poor correlation with surrounding survey marks in the GDA2020 state adjustment. Furthermore, these empirical values may not always be realistic, particularly under challenging observing conditions.

Then we calculated PU individually for each NRTK observation, based on the coordinate quality (CQ) indicators provided by the GNSS equipment, resulting in overly optimistic values. While a scale factor can be applied to obtain more realistic PU values, this adds statistical guesswork to a process that was intended to be more rigorous than the empirically derived PU estimate. The varying proprietary methods of CQ computation between GNSS receiver makes and models add further complexity to the derivation of a reliable scale factor, and separate scale factors may be necessary for the horizontal and vertical components. NRTK observations continue to be treated as point-based solutions with uncertainties (poor correlation with surrounding marks), and historical data would have to be reprocessed. Consequently, this does not provide a significant advantage over the use of empirically derived values, while adding a degree of complexity.

Generating a NRTK baseline network

NRTK observations are generally treated as point-based solutions with VRS data being discarded after computation, which causes issues when attempting to incorporate NRTK observations and their uncertainties into a least squares network adjustment. Our new approach overcomes this issue by exploiting the automatically computed GNSS baselines between NRTK observations and their VRS to create a connected network.

Depending on fieldwork practices, multiple observations share a common VRS and are therefore linked by GNSS baselines. A VRS generally remains active until the GNSS rover is turned off or moves more than 5 km away, i.e. a typical NRTK survey usually exhibits a high degree of connectivity. These connections potentially allow PU values to be rigorously computed via least squares analysis, facilitating simple integration of NRTK data into the GDA2020 state adjustment.

While the VRS coordinates are computed from surrounding CORS data (with the CORS forming the backbone of the datum), it can be argued that the VRS itself is technically not connected to the datum. However, the VRS can be treated as a pseudo-datum station, with the connection to datum completed by deriving a baseline from each VRS to the nearest (or multiple) CORS.

Following the philosophy applied by the Intergovernmental Committee on Surveying and Mapping (ICSM) for including National GNSS Campaign Archive (NGCA) data in the national GDA2020 adjustment, a connection to the two nearest CORS is used here. It is important to note that these derived baselines are not observations, but simply joins used to connect the VRS (and thus the survey) to the datum and to transfer the uncertainty of the datum connection through to the survey network in the adjustment.

As such, this approach employs the automatically computed GNSS baselines between NRTK observations and their VRS together with a derived join between each VRS and the two nearest CORS to create a connected network that is adjustable like a traditional, static GNSS network (Figure 1).

Putting theory into practice

We can illustrate this approach by investigating a typical urban NRTK survey conducted by DCS Spatial Services, incorporating 126 observations on 62 marks in Sydney. Best practice guidelines were followed, with each mark occupied at least twice, at least 30 minutes apart, and for a minimum of 2 minutes. Using multiple occupations on each mark adds redundancy, strengthens network geometry and helps minimise outliers. The resulting network exhibited a high degree of connectivity through the baselines automatically generated between VRS and observed mark. While the user has limited control over the network geometry created in this way, the network can be processed akin to a static GNSS survey.

In order to perform a least squares adjustment and allow this survey to influence and be influenced by the datum, it must be connected to it. In this case, six control marks that are part of the GDA2020 state adjustment were observed to provide this datum connection, leaving 56 marks to be adjusted. However, considering that a new VRS is generated when the instrument is turned off or moved more than 5 km from its original VRS location, some marks can potentially become isolated (or disconnected) from the network and datum.

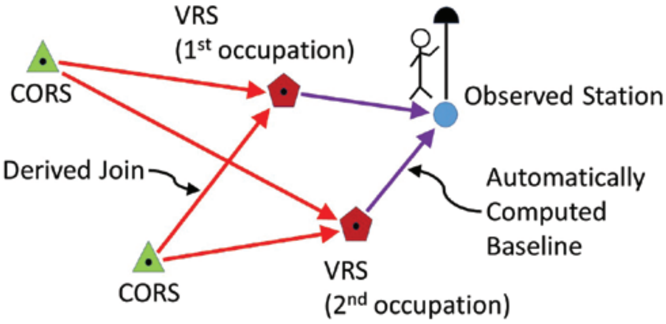

Figure 1: NRTK automatic baseline network being connected to datum via a join between each VRS and the two nearest CORS.

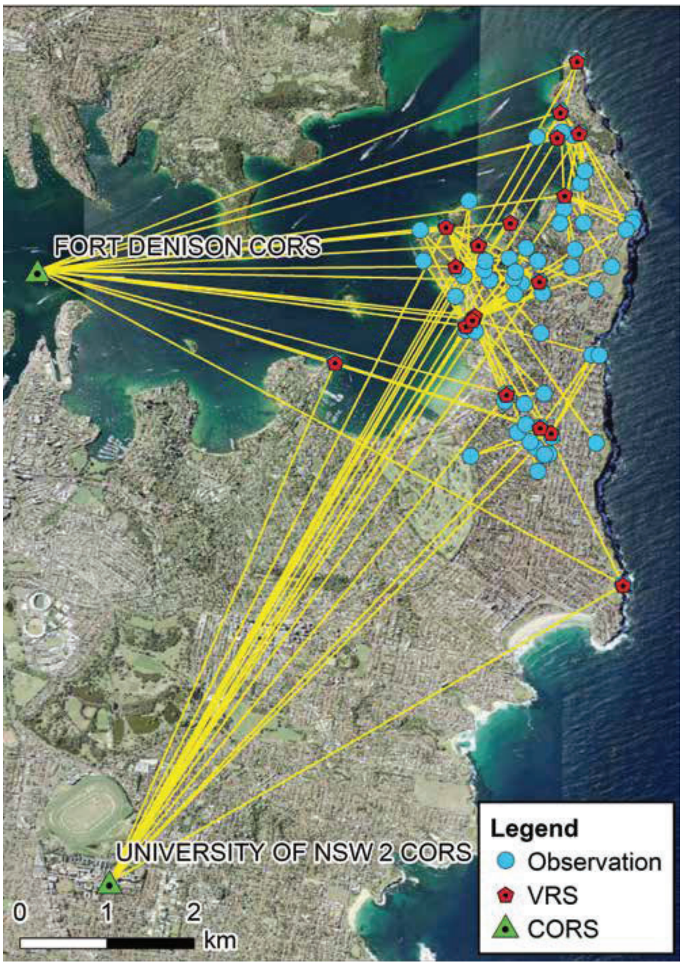

Figure 2: NRTK baseline network including the joins from each VRS to the two nearest CORS.

To ensure connection of all marks to the network, the VRS were treated as pseudo-datum stations joined to the nearest two CORSnet-NSW sites, which were then also constrained in the adjustment (Figure 2). We adjusted this survey network separately to the GDA2020 state adjustment to analyse the statistical results produced by this approach and to obtain preliminary values of PU. These PU values will be updated when this network is incorporated into the GDA2020 state adjustment.

The determination of NRTK uncertainty based on modelling the contributing errors is an ongoing area of research (e.g. Baybura et al., 2019; Ouassou and Jensen, 2019; Jongrujinan and Satirapod, 2020). In this case, baseline weightings were chosen to mimic the standard deviation values (1σ) routinely applied by DCS Spatial Services for NRTK uncertainty in practice: 0.014 m (horizontal) and 0.030 m (vertical). These values include allowance for to/from centring errors and have proven realistic in most practical observing conditions using CORSnet-NSW. While it is known that NRTK observations exhibit a small degree of distance dependency, recent studies have found no significant effect for NRTK solutions located up to 40-50 km from the nearest CORS (Gökdas and Özlüdemir, 2020). Consequently, residual NRTK distance dependency can be ignored in this case.

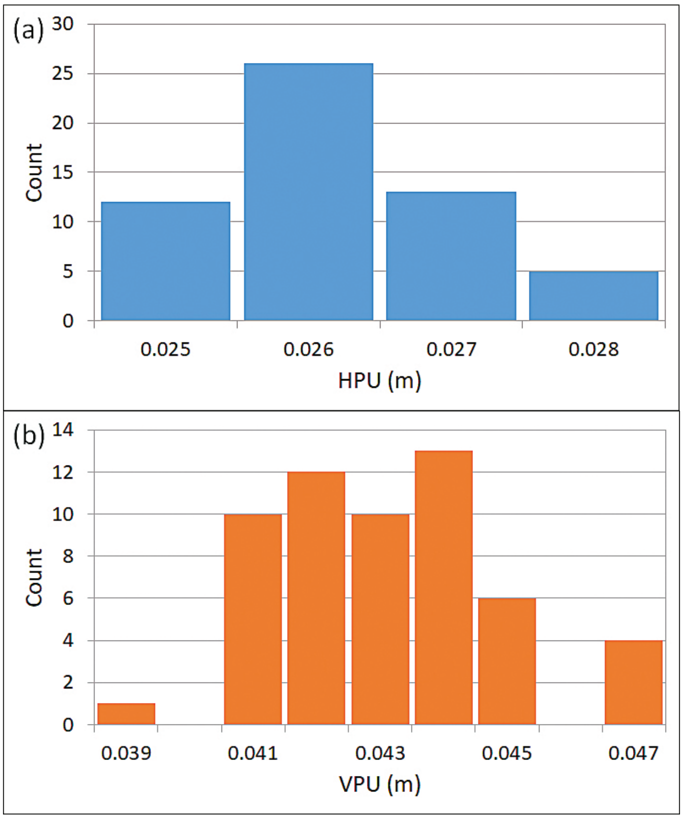

Figure 3: Calculated (a) HPU and (b) VPU for NRTK observations based on the NRTK baseline network.

Table 1: Descriptive statistics for HPU and VPU, calculated based on the NRTK baseline network for 56 adjusted marks (all values in metres).

Descriptive Statistic	HPU	VPU
Minimum	0.025	0.039
Maximum	0.028	0.047
Mean	0.026	0.043
Median	0.026	0.043
Standard Deviation	0.001	0.002

Since each observation is connected to the datum by two baselines (i.e. CORS to VRS and VRS to occupied mark) and to avoid inflation of the uncertainties through this join in the adjustment, these initial values were divided by √2 according to the error propagation law. This resulted in final weightings of 0.010 m (horizontal) and 0.021 m (vertical) for each baseline, with no distance dependency applied.

As previously mentioned, the two CORS served as constraints in the fully constrained adjustment, along with the six GDA2020 control marks that braced the network. The median HPU of these eight constraints was 0.018 m, and the median VPU was 0.026 m. The adjustment achieved a variance factor of 0.9, which is expected for a network of this nature. In this case, as a business rule, DCS Spatial Services does not tighten the input standard deviations to achieve a variance factor of unity. Histograms of the resulting PU values are shown in Figure 3, while corresponding descriptive statistics are summarised in Table 1.

The adjustment provided individual uncertainties for each NRTK observation, with median values of 0.026 m (HPU) and 0.043 m (VPU), i.e. about 0.010 m and 0.015 m better than the empirical estimates obtained earlier. This can be explained by improved geometry and redundancy due to the network adjustment. These preliminary results demonstrate the appropriateness of the observational weighting strategy used and that this method can provide reliable results. Current work investigates tweaking the observational weighting strategy to optimise the inclusion of NRTK observations with realistic uncertainties in the GDA2020 state adjustment.

Conclusion

Australia's new national datum, GDA2020, is based on a single, nationwide least squares network adjustment that rigorously propagates uncertainty. As the GDA2020 state adjustment continues to grow, efforts are underway at DCS Spatial Services to further increase user access to Positional Uncertainty for survey marks on public record in NSW.

This paper has described the GDA2020 state adjustment and presented a new approach to include NRTK observations and their PU in the NSW survey control network via the GDA2020 state adjustment. We employed the automatically computed baselines between NRTK observations and their VRS, combined with a derived join between each VRS and the two nearest CORS, to create a connected network that can be adjusted akin to a static GNSS network. Using a typical urban NRTK survey in Sydney as an example, PU was calculated to be about 0.026 m (HPU)

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and 0.043 m (VPU), comparing reasonably well to empirical positioning quality and user experience.

This approach provides a rigorous method of computing realistic PU and allows easy integration into the GDA2020 state adjustment, while maintaining the quick and easy nature of NRTK positioning. These benefits come at no expense to fieldwork time or complexity. The processing load is only marginally increased (network adjustment rather than site transformation), once CORS-to-VRS baseline derivation is automated. The need for each historical NRTK survey to be adjusted separately is a reasonable price to pay for this comprehensive solution.

Adoption of this methodology will allow NRTK data to be rigorously included in the GDA2020 state adjustment, enabling DCS Spatial Services to further maintain and improve the NSW survey control network for the benefit of all.

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