The 2022 GNSS Survey for a New International Great Lakes Datum: Overcoming Challenges with International Planning and Digital Tools

Ryan HIPPENSTIEL, John MAY, and Jacob HECK, United States, Michael CRAYMER and Rachel VAN HERPT, Canada

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SUMMARY

The Great Lakes region in the United States and Canada is home to one of the largest surface freshwater resources on earth. It is a dynamic environment that is influenced by crustal motion due to glacial isostatic adjustment (GIA) as well as short and long-term environmental factors. The International Great Lakes Datum (IGLD) is a joint product developed by the binational Coordinating Committee on Great Lakes Basic Hydraulics and Hydrologic Data to account for these changes and provide a consistent water level datum across the entire Great Lakes and St. Lawrence River region. In 2022, NOAA'S National Geodetic Survey (NGS) and Natural Resources Canada's (NRCan) Canadian Geodetic survey (CGS) conducted a GNSS survey across the region to observe over 350 bench marks located at or near water level stations throughout the Great Lakes region both in Canada and the United States. The coordinates derived from this survey, combined with geodetic leveling ties between bench marks and water level sensors conducted by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) and the Canadian Hydrographic Service (CHS), will provide consistent ellipsoid heights on water level gauges, tying the water level stations into the new IGLD (2020) datum. In addition, the survey will help determine vertical velocities of water level gauges to assist in developing a crustal movement model. The GNSS survey campaign required immense planning, equipment, and personnel to complete within a 6-week window coordinated between both countries. Strict survey protocols were developed for both observers and managers to provide quality control and quality assurance (QA/QC) in near real time. Both of these steps were heavily supported by leveraging digital tools to plan, conduct, and visualize the GNSS survey. Additionally, NGS field staff and managers employed a mobile application and a data-rich GIS web map to implement and monitor the survey results. The survey's success will lead to project completion and provides an example to follow for future campaigns of similar complexity and magnitude.

1. BACKGROUND/PURPOSE

In 2022, federal government geodetic agencies from Canada and the United States conducted a 6-week static GNSS surveying campaign with observations on about 350 bench marks in support of the development of a new International Great Lakes Datum (IGLD). IGLD is a binational, joint effort designed to provide a consistent reference for elevations across the whole region. This region is influenced by glacial isostatic adjustment (GIA) which causes a tilting across the basin due to vertical land motion that results from the melting of the ice sheet over Hudson Bay during the last ice age. Due primarily to the effects of GIA, IGLD is updated every 25-35 years. The previous update was IGLD (1985), which was made available in 1992. The Coordinating Committee is in the process of developing the next IGLD, IGLD (2020), which is expected to be made available around 2026. In addition, both Natural Resources Canada's (NRCan) Canadian Geodetic Survey (CGS) and the U.S. National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) are currently modernizing national horizontal and vertical datums for Canada and the U.S. respectively. The timing of the IGLD update will allow for a close relation to the new national vertical datum to be adopted, the North American – Pacific Geopotential Datum of 2022 (NAPGD2022).

The overall datum update is a lengthy process requiring coordination and agreement between Canada and the United States, which was historically formalized with the creation of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. Within this committee, the Vertical Control-Water Levels Subcommittee was tasked with the implementation of the IGLD, including the revision of previous versions when necessary. The current update to IGLD requires coordination between federal agencies responsible for geodetic surveying, transportation infrastructure, and water level measurement. Over the course of about 10 years, these agencies are tasked with determining datum parameters, collecting water level data through maintained stations, conducting the current GNSS campaign, and performing analysis to produce hydraulic correctors and align the IGLD to modernized reference frames and models. Specific to the GNSS survey discussed here, 4 campaign surveys have been performed prior to the 2022 survey (in 1997, 2005, 2010, 2015), and an additional survey will be performed in 2027 to validate velocities determined through the analysis of the previous 5 iterations.

After the 2015 survey, geodetic and water level agencies from both nations began preparations for the 2020 survey as it would be conducted at the 2020 reference epoch for the new IGLD. This survey would require GNSS observations on bench marks at all of the permanent water level stations, and additionally, at seasonal water level stations installed (or to be installed) from 2016-2024. These seasonal water level stations are normally installed for one observing season over the course of the seven year water level observing period, and serve to densify the permanent station network for analysis of hydraulic correctors. Each water level station was to be tied to their local bench mark network via geodetic leveling, and this work was conducted by the Fisheries and Ocean Canada's (DFO) Canadian Hydrographic Service (CHS), Environment and Climate Change Canada's (ECCC) National Hydrological Services (NHS), Natural Resources Canada's (NRCan) CGS, and NOAA's Center for Operational Oceanographic Products and Services (CO-OPS). As the plans developed and this work continued, a planning group coalesced to ensure work was on track and assist with the coordination of the selection of bench marks for the GNSS campaign. This was necessary to ensure that geodetic leveling ties from the water level stations included the specific bench marks that would be surveyed with GNSS receivers. This group consisted of team members from various federal agencies within both Canada and the United States.

Canadian Partners	**United States Partners**
NRCan - Canadian Geodetic Survey (CGS)	NOAA – National Geodetic Survey (NGS)
DFO - Canadian Hydrographic Service (CHS)	NOAA – Center for Operational Oceanographic Products and Services (CO-OPS)
ECCC - National Hydrological Service (NHS)	US Army Corps of Engineers (USACE)
Ontario Power Generation (OPG)	Michigan Department of Transportation (MDOT)
Saint Lawrence Seaway Management Corporation (SLSMC)	New York Power Authority (NYPA)
Hydro Québec (HQ)	Great Lakes St. Lawrence Seaway Development Corporation (SLSDC)
	Wisconsin Department of Transportation (WisDOT)
	Darin J. Henkel, PLS

Table 1: Planning and Observation Group for the 2022 GNSS Survey

While conducting the previous four GNSS surveys, bench marks at only the permanent water level station locations were included, with some additional and redundant bench marks included. The number of bench marks observed during those 4 survey campaigns ranged from 51-98 in the US and Canada, with the surveys taking approximately 3-5 weeks. The planning team knew that the 2020 survey would include seasonal bench marks and possibly stations operated by partners, which would double or triple the effort needed. The team continued to virtually meet regularly, increasing the frequency of meetings leading up to the beginning of 2020, in which the COVID-19 pandemic dynamically altered the overall progress of the IGLD survey campaign. Initially there was hope the survey could still be conducted, but as the world found out, the magnitude of the emergency was larger than originally anticipated. Meetings during this time not only included the project scope, but pivoted to an assessment of each agency’s operational status as it related to the pandemic. This assisted the entire team in helping determine when rescheduling the 2020 survey could be completed. This discussion carried on through 2021 and into 2022 before it was determined that each agency was capable of deploying field crews at the end of the summer of 2022. The reason that the above decision was made on a yearly basis was to stay consistent with the timespan previous surveys had been conducted, largely avoiding the spring wet conditions which can cause loading effects and height differences from normal levels.

2. ACCURACY

Because there are many datasets that ultimately go into building the IGLD, each component being completed as accurately as possible is critical. Without high accuracy in each and every data set, there can be a cumulative sum of error that is not allowable for the overall datum. The desire for the GNSS campaign was to achieve roughly 2 cm of accuracy at each bench mark surveyed. As GNSS users know, each observation, baseline, and site conditions can be unique, so the project would not be deemed a failure if there were outliers among nearly 400 bench marks surveyed, but conditions were put in place to try to minimize this possibility. The factors behind achieving the best result with GNSS are fairly well known among surveyors and geospatial professionals. The length of observation, proper use of quality equipment, and availability to communicate with a wide spread of satellites are critical. The last factor of course is what many call ”visibility” or ”a good view of the sky”, which means that the best measurements based on satellite frequencies are achieved with a horizon clear of obstructions such as trees, buildings, and fences. These items can completely block satellite signals, or in some cases, create reflections of the signals called multi-path that degrades the accuracy of the solution. From a practicality standpoint, the latter can sometimes be more dangerous to the field observer because it still allows the observations to continue and the noisiness of such is not known until the data is processed. As one can see, the selection of a good site and use of error-reducing field protocols is important. With all factors considered, it was determined that each observer should perform two static GNSS observations for a minimum of 24 hours each on the water level bench marks assigned to them. This assured both the length of time needed for the desired accuracy and redundancy in data observations to improve the solution and/or minimize loss of data. Twenty-four hour solutions were also advised for seasonal occupations prior to the 2022 survey.

3. BENCH MARK SELECTION

Final site selections continued based upon previous reconnaissance efforts and current information on previously-selected bench marks. Due to the delays, there were sites in which significant time had passed since the initial reconnaissance efforts which potentially led to a number of changing site conditions. A major effort was initiated by leveling crews from CO-OPS, NGS Regional Advisors, CHS, WSC, and other federal and state/provincial partners to provide the overall team a more recent report of the condition of each bench mark. In cases where bench marks were destroyed (by construction, relocation, vandalism) or where the site conditions were not ideal for GNSS observations (due to new obstructions or access issues), CO-OPS field crews set new bench marks while conducting leveling assignments and provided the information to the GNSS field observers. Bench marks were selected based upon stability, historic GNSS use, satellite visibility, safety, security, and convenience. For stability, it was defined that bench marks should be Stability code A or B, based on NGS standards (Bossler, 1984; NOAA, 1994), which means they are most to moderately reliable and will or probably hold their elevations well. For historic GNSS use, the team looked for the presence of a NAVD88 height, past use of the bench mark, and probability that the bench mark would be available for GNSS observations in the future. For satellite visibility, a horizon clear of obstructions is ideal for the collection of as much satellite data as possible. It was acknowledged that some sites may not be perfect and that field personnel could use their best judgment if a new bench mark was needed. This decision was not made lightly as it requires both labor and material costs to set a new bench mark, and ideally sufficient time after the bench mark is set for any natural settling to occur. The last factor the planning team considered when setting or selecting bench marks was their location and how that related to access and safety. Many bench marks were in public locations where security had to be considered, and vice versa, as some are on facilities with limited access where field observers may have to deal with working schedules and security protocols. Ideally, a publicly available site that was safe is the best location for a GNSS observation, but in the case where equipment safety was considered at risk, field observers were prepared with lockable boxes and security cables to try to ward off tampering. Site selection was largely completed through regular meetings with data compiled from agency records, field reconnaissance, and the previous GNSS surveys. To allow the planning team to communicate and act on new information, a master spreadsheet was created with station information as shown below. In addition to this information, additional tabs provided more detail on specific bench marks, security concerns, and miscellaneous notes.

1	Sort Nc	Gauge Type	Country	Water Body	Station Name	Station ID	Recon 2019-2022	Observer 2022
52	81	Permanent	United States	Lake Erie	Fermi Power Plant	9063090	DONE CO-OPS	NGS
53	82	Permanent	United States	Lake Erie	Toledo	9063085	DONE CO-OPS	NGS
54	83	Permanent	United States	Lake Erie	Toledo	9063085	DONE CO-OPS	NGS
55	~~205~~	~~Seasonal~~	~~Canada~~	~~Lake Erie~~	~~Fort Erie~~	~~12950~~	~~NO~~	~~NO~~
56	206	Seasonal	Canada	Lake Erie	Port Maitland	12800	DONE CHS-ON	CGS/CHS
57	207	Seasonal	Canada	Lake Erie	Port Rowan	12615	DONE CHS-ON	CGS/CHS
58	208	Seasonal	Canada	Lake Erie	Port Burwell	12500	DONE CHS-ON	CGS/CHS

Table 2: Excerpt from Planning Spreadsheet

4. SPECIFICATIONS

Parallel with the site selection planning was an effort by team members to ensure the accuracies of the project were met through binational specifications for the GNSS survey campaign. These specifications detailed the requirements for bench mark selection, observation length, and sky visibility previously mentioned, but also served to lay out expectations for equipment preparation and the metadata to be collected. The latter items are critical for proper data collection and the ability to process it thoroughly with rigorous routines after the survey campaign. To maintain a high standard of quality of observations, geodetic-quality GNSS equipment was used by all partners for each observation. This high accuracy is achieved by ensuring receivers are dual frequency with a minimum of 10 channels

Figure 1: Photo taken at Grand Marie, Minnosota. Located on Lake Superior

for tracking GNSS satellites, and ideally be able to collect multiple satellite constellations in order to maximize the number and coverage of satellites available at any time and location. The antennas either featured a choke ring and/or absolute phase center calibration in the International GNSS Service (IGS) or NGS database. It was also determined that some of the new integrated receiver/antennas should not be used due to the lack of ground planes and potential susceptibility to signal multipath. While setting up the antennas, all observations would be collected on a fixed height mast or tripod, with no observations to be collected with slip-leg tripods unless under special circumstances due to an irregular survey mark. Using fixed height masts/tripods eliminates errors in measuring the height of the antenna above the bench mark. The processes for stabilizing this equipment is slightly different as the masts used at permanent locations in Canada are tethered with chains and anchoring bolts or cork screw stakes, whereas the fixed height tripods primarily used for ground bench marks in the United States are weighed down with sandbags on the feet of each tripod leg. To maintain precision, the tips of all of these pieces of equipment must be protected so they do not get bent and inspected throughout the survey. Adjustable fixed height tripods were also allowed as they work well in the instance of a bench mark that is elevated above the ground. These tripods can be set at three different fixed heights to provide the observer flexibility. Each mast/tripod was calibrated by each geodetic agency prior to the campaign and the heights were later recorded by the observers on observation logs collected in the field.

Specific to the GNSS receivers, configuration parameters were advised to provide consistency between all agencies to maximize accuracy in the observations. A collection rate of 30 seconds was decided upon, along for 15 seconds if the receiver or observer required it. The 30 second rate ensured that ample epochs were collected without greatly increasing the size of the observation data file. Modern GNSS receivers are capable of extremely high collection

Figure 2: Photo taken at Killarney, Ontario. Located on Georgian Bay (Lake Huron)

rates, though with 24-hour observations, they can create very large data files. Extremely large data files can create issues with receiver storage, data transfer, and post-processing. With a reasonable collection rate assigned, the planning team also encouraged a minimal elevation mask for observations. Elevation masks are typically applied to cut out observations below a certain angle of the horizon to eliminate noisy signals due to obstructions. However, utilizing an elevation mask will also remove signals that are of sufficient quality especially if a good site has been selected. For this project, an elevation mask of 0 degrees was preferred, but 5 degrees was allowable if the observer had known obstructions that the mask might help to remedy. The reasoning behind this decision was to allow for all observations possible to be collected and any noisy observations could be removed with post-processing. Overall, the above specifications were agreed upon, documented, and distributed to all field observers. Further specifications as they relate to field protocols are discussed later.

5. SCHEDULING

With an agreed upon scope and rough time period determined, the planning team started to select final dates of survey observations. This included both the dates of the observations, as well as daily start and stop times. The latter is critical as GNSS baseline processing is more effective when simultaneous observations are collected. The individual sessions were established in pairs to allow for the two 24-hour static observations. The starting time of the 24 hr occupations in each session were staggered by 4 hours from the first day to the next to allow a window of time for an observer to break down the first observation, complete the data transfers, and then set up the second independent observation. The protocol of completely dismantling a set of equipment, and ideally, using a completely different receiver and tripod helps reduce the chance of instrument height blunders and bias in certain pieces of equipment. As with all aspects of any GNSS campaign, errors are inevitable, but the goal of the protocol is to reduce error sources as much as possible. As bench mark selection and scheduling efforts ramped up, an ESRI web map was created which helped to visualize bench mark locations and travel times for observers. In some cases, observers were tasked with multiple bench marks if they were in the same vicinity and there was time to deploy multiple sets of equipment. In addition, after both sets of observations on a mark were collected, the individual observer needed to travel to their next general location, often requiring a full day of driving. The web map was key to scheduling the overall campaign as it efficiently displayed the approximate position of permanent and seasonal stations, allowing the planning team to discuss, confirm, and modify survey locations as needed.

Figure 3: First Iteration planning map of permanent and seasonal gauge sites

6. GIS TOOLS

The first iteration of the web map was basic in nature and contained points and best-known locations, but as planning continued, so did the improvement and development of GIS tools to facilitate many aspects of the survey project. For the US observations, NGS further refined an ESRI web map to include the best available positions of bench marks and for access on the observer's mobile device through the use of ESRI Field Maps. The integration of Field Maps into the project workflow provided a number of benefits. Recovery and description information in the geodatabase was instantly available to the field observers. The mobile device location was leveraged for driving directions and finding the bench marks. Additionally, the bench mark features could be edited in real time to allow the field observers to change the observational status of the bench marks. Those changes were reflected immediately and visible to campaign managers. Each bench mark feature was named in the web map to reflect the Four Character Identifier (4CID), the observer and the planned observation date. The bench marks were organized into observer layers which allowed for filtering and decluttering. This visualization also assisted when problems arose during the field survey itself. Field staff were faced with high waters, storms, and bench marks that had been destroyed by construction. Being able to access the map and supporting data sources allowed managers and field staff to select substitute bench marks, redeploy equipment, and coordinate additional resources where needed.

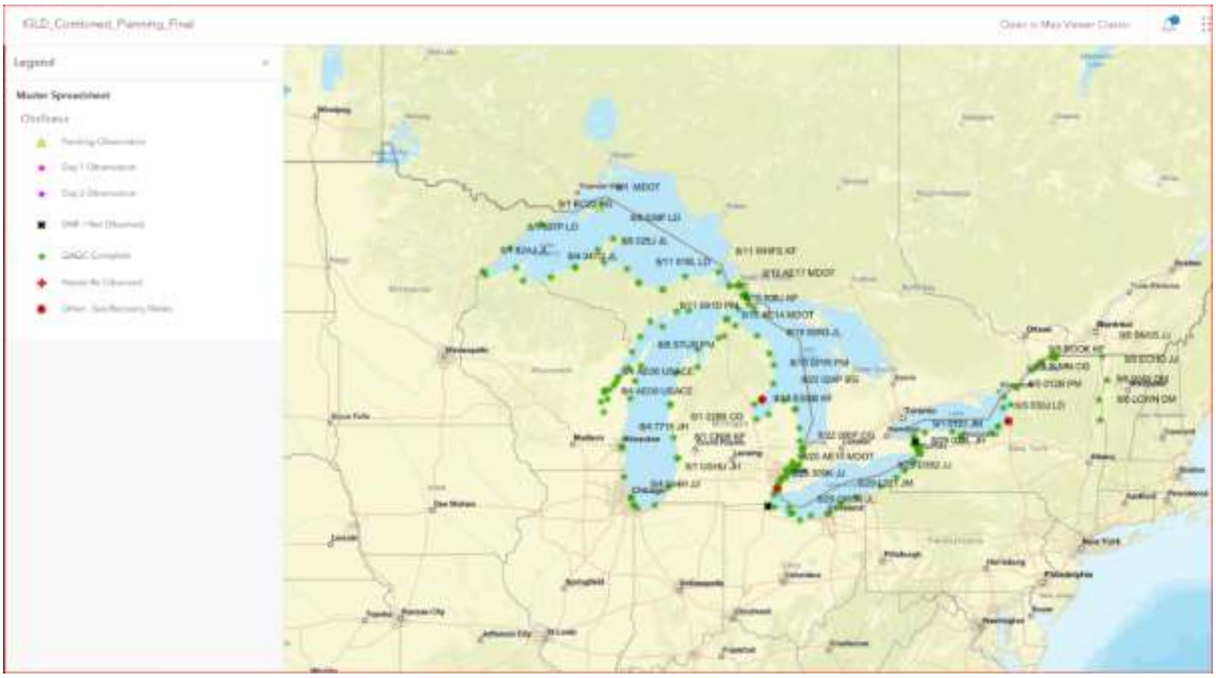

Figure 4: Campaign map of bench marks

After the survey campaign was completed, an ESRI dashboard was compiled by NGS for briefing interested stakeholders. This serves to be an effective way to quickly display the accomplishments by both nations when in meetings, conference sessions, and planning meetings in the future.

Figure 5: Post Survey ESRI Dashboard

7. FIELD CAMPAIGN

With bench mark selection finalized, the exact dates for observations were determined with the goal of trying to keep ”cross-lake” ties even between both nations. This scheduling would provide evenly spaced baselines roughly running north to south across the lakes in common. This created some challenges for carrying out the survey around Lake Michigan, as its many bench marks are all within the U.S. Other smaller complications were the far west end of Lake Superior, around Georgian Bay on Lake Huron, and then continuing north along the St. Lawrence River beyond the Moses-Saunders Hydroelectric Dam in Cornwall, Ontario where only Canadian gauges exist. This was accounted for by NGS starting a week earlier than Canadian agencies, splitting resources between the western end of Lake Superior (3 observers) and Lake Michigan (7 observers). CGS, CHS, and WSC began on August 9th, splitting their resources between the western end of The Great Lakes (8 observers) and the eastern end of The St Lawrence River near Rimouski, Québec and Tadoussac, Québec (5 observers).

Figure 6: NGS personnel configure recievers prior to the IGLD 2020 campaign

Equipment was prepared and protocols were developed to improve the observation, download, and processing of data. Each GNSS receiver was configured with the settings detailed in the survey specifications and were paired with antennas. Each vendor and receiver is unique, but many allow for the ability to ”clone” additional pieces of equipment from a single configuration or startup file. A set of configuration parameters is saved and then loaded into other receivers to speed up the configuration process. Configuring the receivers in advance ensured they would operate consistently and eliminate the need for field observers to set parameters on the fly. In addition to surveying parameters, the receivers were programmed to store observation files in a specific naming convention so that it was easy to identify what receiver was used and on what Julian Day the observation took place.

In addition to GNSS equipment, each field observer was responsible for preparing surveying and recovery equipment required for the project (sand bags, tools, compass, tapes, probes, etc.). Observations commenced on the 1st of August with crews on the U.S. side starting the field cadence of two days of observations and traveling to the next site/bench marks on the third day. The Canadian resources joined the following week and observers started workly roughly west to east, tucking into inlets and tributaries as needed. Along the way, NGS was joined by partners from the US Army Corps of Engineers, the Wisconsin Department of Transportation, and a private sector surveyor to observe bench marks at water level stations belonging to various partner agencies. Adding these bench marks to the survey during the campaign increased GNSS network redundancies and assured that IGLD (2020) values would be computed at those gauges. The Canadian observers were assisted by various public and private sector partners in order to observe bench marks that were not publicly accessible. Field work continued through August, with NGS completing observations on September 10th and Canadian crews worked an additional week to complete stations on the St. Lawrence River that fell solely in Canada and did not have ties to U.S. stations.

Daily routines for field observers included deploying equipment, completing observation logs for bench marks, collecting metadata (obstructions, photographs, bench mark descriptions) all of which were defined during the planning phase. The observation logs, while differing slightly between agencies, were a singular place to document consistent information about the observation. Those include bench mark PID/ID, Bench Mark Designation, observer’s name, bench mark condition, schedule start and end times, tripod/mast height, tripod style, additional offsets to the ARP, antenna height, receiver and antenna models and serial numbers, notable weather conditions, concerns such as obstructions, and power supply information. All of these pieces of information document conditions at the time of the survey, ensure the observer is following protocols, and help troubleshoot anomalies seen during post-processing. For photographs of the bench marks and observations, and for the same reasons as the logs, a standard set of photographs were collected each day. This set of photographs consists of unobstructed pictures of the bench mark itself, and then of the equipment set up in each cardinal direction. These horizon photographs allow a quick documentation of the equipment but also the overall site conditions and sky visibility. Each observer was instructed to report back any problems with the observation and/or the established observation schedule. Each agency had an internal QA/QC process which they utilized to ensure quality through the duration of the survey, though there are general consistencies with how data is downloaded, processed, named, and stored to make transfer and post-processing is streamlined. In all, the survey consisted of ~25 observers over the span of nearly 7 weeks producing 19,193 hours of GNSS observations.

8. OUTCOME

The final data set included GNSS observations and metadata for 365 bench marks, 179 for Canada and 186 for the US. The final deliverables were converted RINEX files for each observation file, ideally totalling a minimum of 48 hours of data, raw observable files saved for potential use in the future, and supporting metadata for each bench mark.

This GNSS campaign turned out remarkably well. Repeatability between station occupations as determined from PPP results was less than a cm for 92% percent of the station occupations. Over the seven weeks of observations, there was no extended downtime due to weather, equipment failures, or other issues. The data were collected successfully, and the next step is to perform the data processing. The Canadian processing team at CGS will use the Bernese GNSS Software software package (Dach et al., 2015), while the processing team on the U.S. side at NGS will use NGS's OPUS Projects (NGS, 2023). The results will be compared for consistency, and final results will be used to bring the positions of the bench marks into the global geometric reference frame. A follow-up survey campaign at only the permanent gauges is being planned for 2027 to validate the results and improve the surface deformation model.

The GNSS campaign is one major step in the development and implementation of IGLD (2020). Seasonal water level gauging continues into 2024 and will be used to densify the permanent water level gauge network to determine so-called hydraulic correctors representing lake surface topography. Hydraulic correctors are used to reconcile the water level observations at each gauge and Roman & Crowley (2023) are investigating the extent to which these will be needed in the updated datum.

The reference epoch for IGLD (2020) will be 2020.0, which is at the midpoint of the 2017-2023 water level collection period. In addition, transformation tools between IGLD (2020) and previous IGLD realizations are being planned to ensure a connection between old and new datums.

Since IGLD (2020) is built upon NAPGD2022, IGLD (2020) is planned for release about one year after the release of NAPGD2022, which means IGLD (2020) will likely be available around 2026. IGLD (2020), like NAPGD2022, will be accessed using GNSS observations along with a geoid model and surface gravity model.

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CONTACTS

Ryan Hippenstiel
NOAA National Geodetic Survey
672 Independence Parkway
Chesapeake, Virginia
UNITED STATES
Tel. +1-240-678-7955
Email: ryan.hippenstiel@noaa.gov
Web site: https://geodesy.noaa.gov/

John May
NOAA National Geodetic Survey
672 Independence Parkway
Chesapeake, Virginia
UNITED STATES
Tel. +1-202-451-1762
Email: john.may@noaa.gov
Web site: https://geodesy.noaa.gov/

Dr. Jacob Heck
NOAA National Geodetic Survey
4840 South State Rd
Ann Arbor, Michigan
UNITED STATES
Tel. +1-202-306-6904
Email: jacob.heck@noaa.gov

Web site: https://geodesy.noaa.gov/

Dr. Michael Craymer
Canadian Geodetic Survey
Natural Resources Canada
588 Booth Street
Ottawa, Ontario
CANADA
Tel. +1-613-791-0157
Email: michael.craymer@nrcan-rncan.gc.ca

Rachel van Herpt
Canadian Geodetic Survey
Natural Resources Canada
588 Booth Street
Ottawa, Ontario
CANADA
Tel. +1-343-543-7168
Email: rachel.vanherpt@nrcan-rncan.gc.ca