Practical Considerations in Implementing a Geoid Monitoring Service

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Key words: geoid, gravity, vertical reference systems, GRACE

SUMMARY

The National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) is planning on incorporating a dynamic geopotential model as part of datum modernization in 2022. This time-dependent model, known as the Geoid Monitoring Service (GeMS), will encompass dynamic versions of a geoid model, a gravity model, deflections of the vertical (DoV), and a digital elevation model (DEM). The overall purpose of these dynamic models is to provide the most up-to-date information to surveyors and other geodetic professionals in order to support disaster management; smart, four-dimensional cities; and spatial infrastructure.

This paper will present the critical aspects of the GeMS project that will eventually be utilized to build, incorporate, and maintain a dynamic geopotential model. These aspects include the relevant geophysical phenomena that cause temporal changes to the geopotential field, how these phenomena behave differently at different temporal frequencies, and some insight into how NGS plans to incorporate GeMS dynamic models into NAPGD2022.

Any mass redistribution of the Earth's material can create changes to the geoid surface and geopotential field. The typical mass changes that drive geoid change at mm-levels are glacial isostatic adjustment (GIA), present day ice-mass changes, changes in hydrology (including ground water storage, snow, etc.), large earthquakes, and volcanic eruptions just to name a few. These phenomena typically have a certain temporal signature being either secular, cyclical, or episodic. For the secular signatures typically associated with large geographic features like GIA, satellite gravity provided by the GRACE and GRACE-FO satellites is ideal to observe these signals.

Ultimately, the magnitudes that NGS expects to see are at the mm/yr level for geoid undulations, microGal/yr level for gravity, milli-arcsecond/yr level for DoVs, and cm/yr level for a DEM. While these magnitudes might seem too small to be of concern, the precision of geodetic instruments and infrastructure is increasing enormously, and it was only a few decades ago that meter level was thought to be enough precision for the geoid surface.

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1. INTRODUCTION

A dynamic geopotential model is one of the more innovate components that users of geodetic infrastructure will begin to see in national geodetic vertical reference systems in the next decade. Due to the extremely accurate 15 year record of temporal gravity provided by the GRACE satellite mission, geodetic agencies throughout the world now have the ability to include this type of information in their vertical reference systems. This paper should serve as a general outline for how the National Geodetic Survey (NGS) anticipates creating and providing a time-dependent geoid model for the U.S. and its territories. This is provided for the benefit of the greater geodetic community to get a glimpse into some of the questions that NGS has encountered while investigating the creation and delivery of such a model. NGS has been investigating how to build, incorporate, and maintain this into the upcoming modernized geopotential datum, North America-Pacific Geopotential Datum of 2022 (NAPGD2022).

A time-dependent geoid model is just one small but critical element within NGS' Geoid Monitoring Service (GeMS). The GeMS project is also investigating how best to monitor shape changes to the geoid into the future through a variety of geodetic observing techniques spanning the entire spectrum from satellite observations to 'boots on the ground' measurements. Additionally, GeMS will provide users of the National Spatial Reference System (NSRS) a number of time-dependent geopotential related quantities including surface elevations, gravity, geopotential numbers, deflections of the vertical, etc. Finally, GeMS will monitor the shape of the geoid into the future.

Some distinction should be made regarding changes to the shape of the geoid compared with monitoring crustal motion of the Earth. There are a great number of applications and geodetic techniques which investigate how the Earth's surface changes. Geodetic techniques such as repeat GNSS observations with CORS or campaign style setups, Interferometric Synthetic Aperture Radar (InSAR), repeat LiDAR surveys, etc. all are strictly providing how (magnitude, rate, duration, etc.) the Earth's crust changes in time (h_p in Figure 1). The vertical crustal changes are possibly related to changes to the shape of the geoid, but not necessarily. Figure 1 illustrates the relationship of these surfaces through their corresponding 'heights' where both the topographic surface (the crust) and the geoid surface are defined to be dynamic in time.

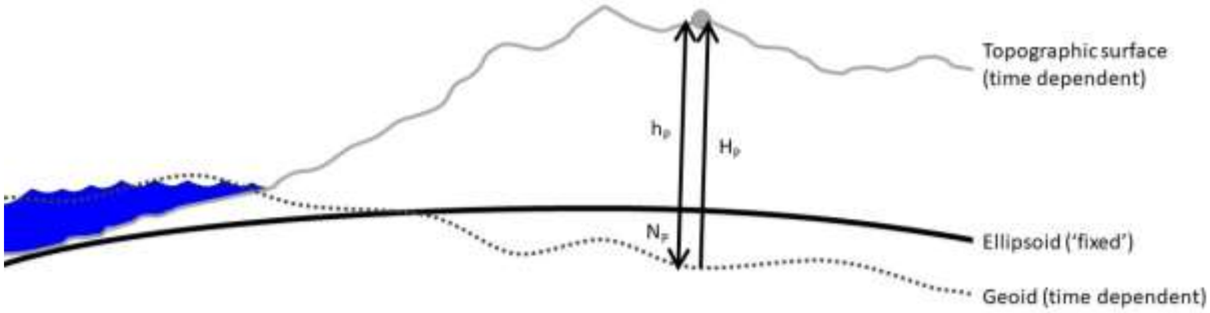

Figure 1: Time dependent surfaces

Geoid change requires enormous movements of mass (see Section 2 for examples). Two examples of this include glacial isostatic adjustment (GIA) over Hudson Bay in Canada and subsidence along the Gulf Coast of the United States. For the Hudson Bay region, additional mass is flowing into the mantle many km's below the crust. This additional material is what is driving the crustal surface change and the geoid change. However, geoid changes are only about 10% of the crustal changes. In the Hudson Bay region for example, CORS vertical velocities ($\dot{h_p}$) are approximately 1 cm/yr while geoid rates ($\dot{N}_p$) are 1 mm/yr. The United States' Gulf of Mexico coastline region (certain areas in the states of Texas, Louisiana, Alabama, and Florida) is also experiencing vertical crustal motion with subsidence rates from CORS in the range of 3 to 6 mm/yr. Geoid rates are very small though in the range of -0.2 mm/yr. This is a result of the subsidence being mostly compaction of the surface material and very limited addition or removal of mass.

This paper will provide a brief overview of the geophysical phenomena that are large enough to warrant inclusion in a GeMS product including how those phenomena behave across space-time, some of the potential product types that GeMS could provide, how to incorporate episodic events (volcanic eruptions, earthquakes, large landslides, etc.) into the reference system, and how updates to the model will take place in the future.

2. CAUSES OF GEOID CHANGE AND THEIR SPACE-TIME SIGNATURE

There are thousands of constantly occurring geophysical processes that cause changes to the Earth's mass distribution. Theoretically, any process that causes Earth to undergo mass redistribution can cause shape change to the geoid surface. Some of these processes include GIA; changes in hydrologic loading due to precipitation, snowfall, and water storage; changes in present day ice sheets; volcanic eruptions; earthquakes; landslides, etc. Luckily, most of these processes are so small in geographical extent and magnitude that they have no noticeable (when viewed from the surveyor's or geodesist's perspective) impact on the shape of the geoid. As illustrated in Figure 2, the largest geoid change globally occurs in areas impacted by GIA (Hudson Bay in North America and Fennoscandia) and present day ice-mass changes (Greenland, Antarctica, Alaska).

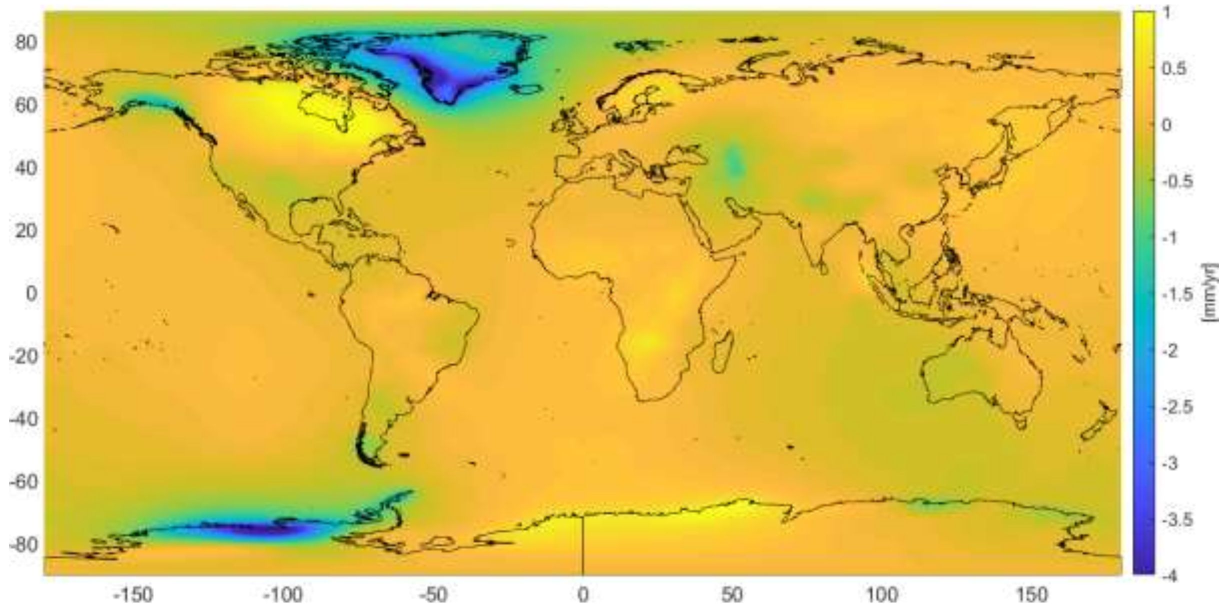

Figure 2: Global geoid time rate of change observed from GRACE (GSFC v02.4 solution) [mm/yr]

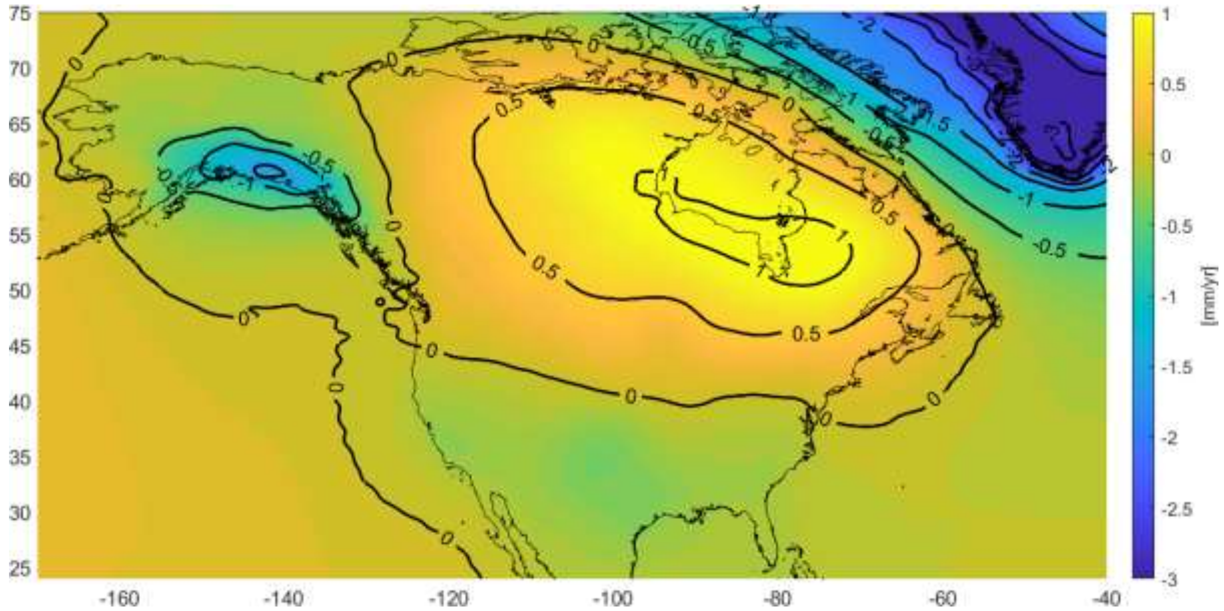

Figure 3: North America geoid time-rate of change observevered from GRACE (GSFC v02.4 solution) [mm/yr]

These processes occur at different temporal frequencies where the phenomena and resulting geoid change could be secular, cyclical, or episodic. The most critical processes to a GeMS product along with examples and magnitudes are shown in Table 1.

Table 1: Geophysical Events that cause shape changes to the geoid (adapted from NGS, 2017)

Temporal Frequency	Temporal Duration	Example	Example Location	Approximate Magnitude	Spatial Scale
Secular	Permanent	GIA	Hudson Bay, Fennoscandia	1.2 mm/yr	> 100 km
		Ice-Mass gain or loss	Alaska	2 mm/yr	
			Greenland	5-6 mm/yr	
Secular	Permanent	Slowing of Earth's spin rate	Pole to equator	8 x 10^{-17} mm/yr	Pole to equator
Cyclical	Permanent	Annual/Seasonal water cycles	SE Alaska	Annual amplitudes ~ 4 mm	~100 km
			Amazon basin	Annual amplitudes ~12 mm	
Episodic	Permanent	Earthquakes (M8+)	Alaska, 1972 (Mw9.2)	12 mm	< 100 km
			New Zealand, 2016 (Mw7.2)	4-5 mm	
Episodic	Temporary	Drought/Deluge	NA	NA	NA

2.1 Secular Temporal Frequency Events

The secular processes are clearly evident in the previous Figure 2 and Figure 3. Monitoring and including the secular signal in a GeMS model provides the majority of the geoid change signal. Additionally, the secular geoid change signal can be separated into components driven by GIA and present-day ice-mass changes. There is a small remaining secular signal which is typically caused by long term hydrology trends (e.g. a 10 year drought over a region) but could be any number of other medium to long term trends. Due to the long wavelength signature (> 100's km), most of the secular signal can be observed by satellites in polar orbit. The NASA/GFZ gravity satellite missions, GRACE and GRACE-FO, are both specifically designed to monitor spatial-temporal changes in the Earth's gravity field. GRACE and GRACE-FO provide very accurate gravity information at long wavelength on a nearly global level. Additionally, a fairly long and consistent time series has been observed with GRACE in operational mode from 2002 – 2017 and GRACE-FO from 2018 – present. There is a roughly 1 year data gap between the missions but the continuity is likely to be maintained into the future. A number of international groups provide Level 2 GRACE products that can be used to build a time-dependent model of the geoid. This paper utilizes the monthly mass concentration solution provided by NASA Goddard Space Flight Center (GSFC), (Luthcke, *et. al.* 2013). These solutions are provided in 1 degree grids of mass change in water equivalency. In order to produce a global, secular, time-dependent geoid model, the trend for each grid in water equivalent mass change is estimated over the entire time span. Figure 4 shows the time series for a 1^o block in the Hudson Bay region of Canada. We use of a fairly simple model to robustly fit the mass change over the entire time span for each block by estimating 4 parameters based on the general equation shown in equation (1) (from Bevis and Brown, 2017).

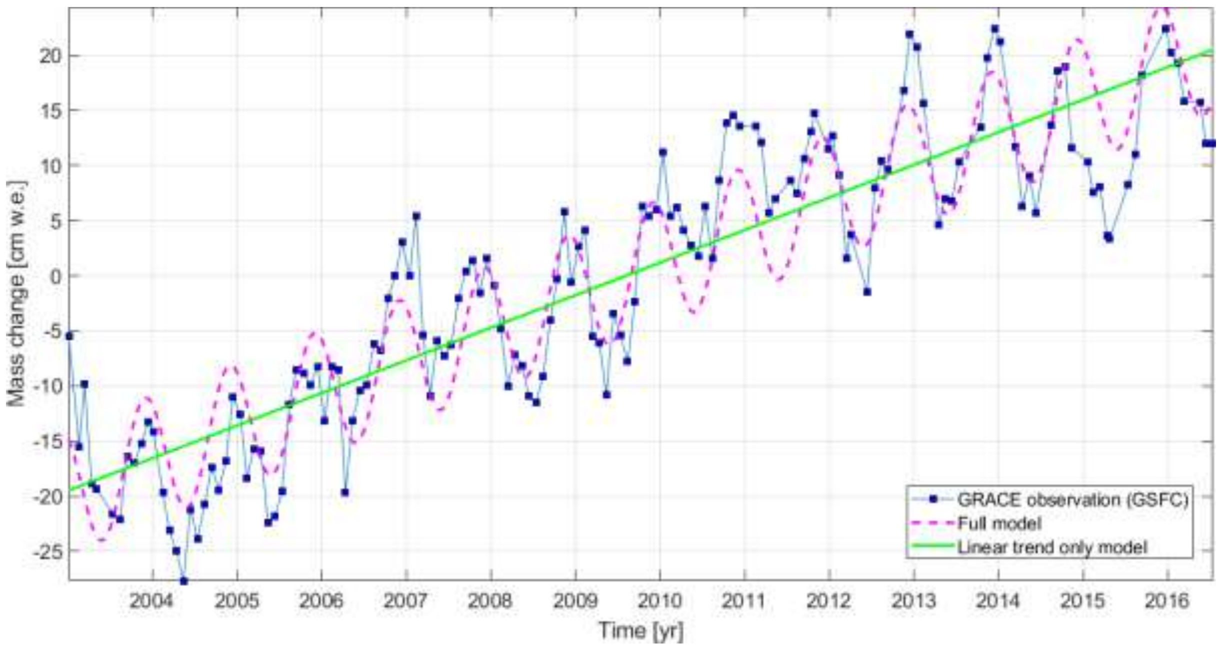

Figure 4: Mass change in cm w.e. from v02.4 GSFC mascon solution for a 1^o x 1^o block in the Hudson Bay region of Canada. GRACE derived mass change observations shown in blue. The full model shown in pink based on (1). The secular trend component based on (1) shown in green.

$$a_0 + a_1 t + \sum_{k=1}^{n_F} [s_k \sin(\omega_k t) + c_k \cos(\omega_k t)] \quad (1)$$

where: $\omega_k = \frac{2\pi}{\tau_k}, where\ \tau_1 = 1\ year, \tau_2 = \frac{1}{2} year, \tau_3 = \frac{1}{3} year, \ldots$

Only an annual term is estimated in this model so $n_F = 1$ and $\omega_1 = 2\pi$. The global grid of secular mass changes is shown in Figure 5. For a more detailed look at the regional level, Figure 6 shows just North America.

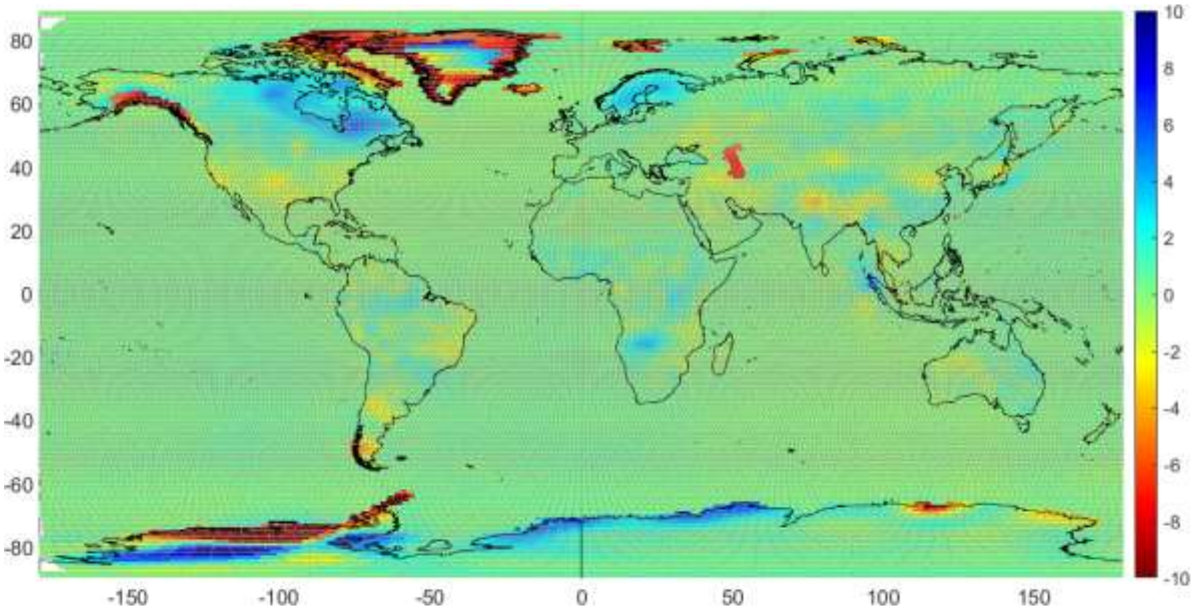

Figure 5: Global secular mass change from GSFC (v02.4) in cm w.e./yr

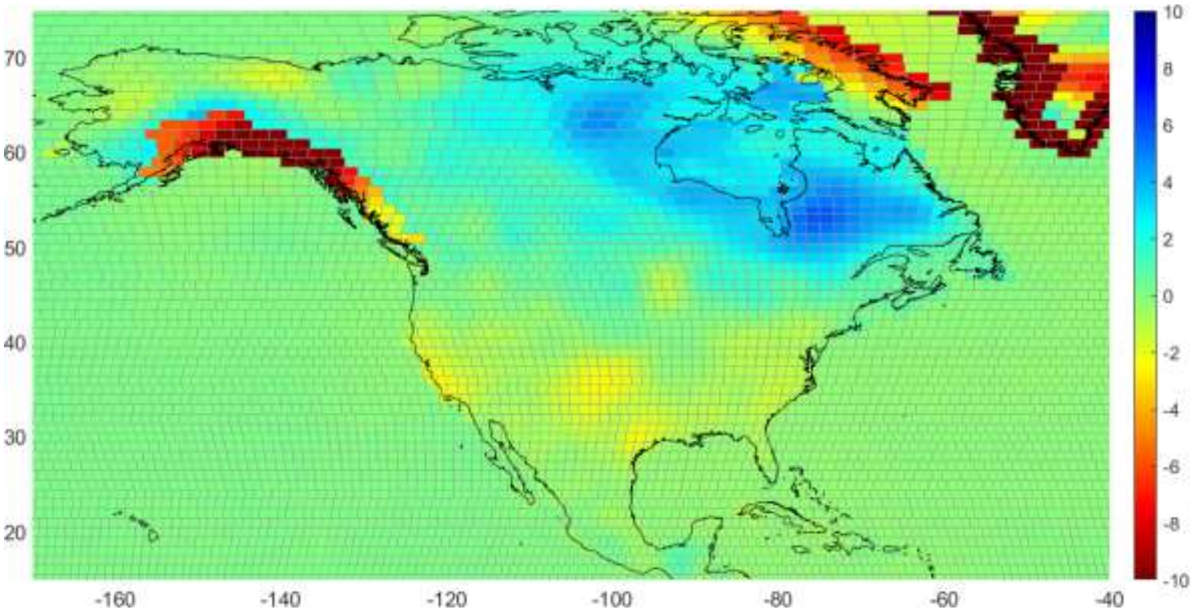

Figure 6: North America secular mass trend from GSFC (v02.4) in cm w.e./yr

The global 1° grid of secular mass changes can then be spherically analyzed resulting in a set of coefficients (c_{nm}/s_{nm}) with $n_{max} = 180$ and then converted from mass trend coefficients into geopotential trend coefficients in the spectral domain based on Wahr, et al. 1998.

2.2 Cyclical Temporal Frequency Events

It should come as no surprise that processes that operate on seasonal or cyclical frequencies also have the capability change the shape of the geoid. The loading due to hydrology changes (in the air, on the surface, below surface, and as ice) is the largest process impacting the shape of the geoid over cyclical frequencies and is mostly contained in an annual signal. This cyclical signal is clearly evident in the mass change time series shown in Figure 4. Slightly less evident is how the cyclical mass change propagates into cyclical geoid change. Figure 7 shows the annual amplitude of geoid change globally. Clearly, the annual hydrological loading in the Amazon River basin is present with peak geoid annual amplitudes at 12+ mm. For areas within the NAPGD2022 coverage area, peak geoid annual amplitudes are in the 4-5 mm mostly in Southeast Alaska and Northwest Canada. At the 4-5 mm level, the cyclical effects most likely do not need to be included in a mathematical model for the geoid. At any time during the year, one would only be 4-5 mm away from the 'true' geoid undulation, which is right at NGS' threshold level of signal to capture (1/2 of 1 cm = 5 mm). Other geopotential related quantities may need to include the annual signal/terms and needs further investigation. Additionally, time-dependent geoid models developed for other parts of the world (like South America and Southeast Asia) where the annual amplitude is larger should definitely consider how impactful including or omitting that annual signal would be.

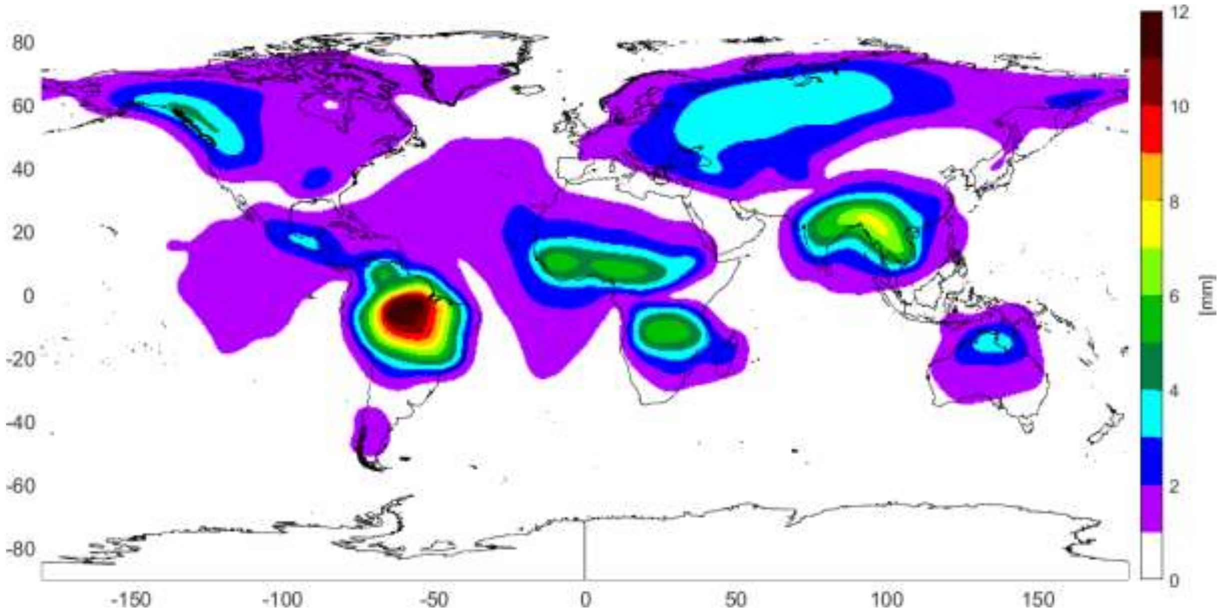

Figure 7: Annual Amplitude in time dependent geoid from GRACE [mm]

2.3 Episodic Temporal Frequency Events

As shown in Table 1, there are a number of potentially catastrophic events (earthquakes, volcanoes, landslides, etc.) that could permanently deform the geoid surface. These events are extremely rare but do occur every few years around the world. The temporal signature of these events can be represented as a Heaviside function or step function. The time signature is quite different from a secular, linear motion that is present for many years (e.g. signal due to GIA) and needs to be incorporated into the geoid time-rate of change model. While the same mathematical models can be employed, this is a significant change for a geoid model. This is not something new to geodesists as CORS GNSS time series analysis often considers the possibility that 'steps' are present in the time series and includes them into the modeling.

At this point, the geoid change and the CORS GNSS time series change due to an episodic event diverge. In the case of CORS GNSS time series, the GNSS receiver providing vast amounts of redundant information about its position and a mathematical model to describe the motion is quite simple to create. In the geoid change case, we have almost no data to rely on and utilize to build a model. There are a very limited number of continuously operating absolute gravimeters around the world that when combined with GNSS would provide some insight on how the geoid shape changed. In most cases, the episodic event would cause a relatively small geographic signature (10 – 100 km) in the gravity field and would likely not be observed adequately from satellite gravity (GRACE-FO, GRACE-2, etc.). For these reasons, it is likely that a geodetic response field campaign would need to be deployed in order to measure the geoid change and build into a model.

This has been done a number of times recently. After the 2016 Kaikoura (Mw7.8) earthquake, a geodetic rapid response occurred to measure gravity and surface changes via GNSS and InSAR (Fukuda, et al., 2018). Additionally, Land Information New Zealand (LINZ) incorporated the surface changes due to the earthquake into their NZGeoid model to assess how the shape of the geoid changed (McCubbine, personal communication, 2018). Over the entire Kaikoura region, changes in the geoid were at 0.5 mm std. dev. but reached magnitudes of 4-5 mm in the areas where surface deformation was largest (5-10 m of uplift). Jacob, et al. 2012 included an investigation into geoid changes due to past earthquake events in North America. They found that only the large subduction induced earthquakes would create a large enough (~1 cm geoid change) to be concerned about. For example, the 1964 Alaska earthquake (Mw 9.2) was estimated to change the geoid by a maximum of 11.7 mm (Figure 8a). This is in comparison to the 1992 Landers (Mw 7.3) earthquake, which caused an estimated maximum geoid change of approximately 0.15 mm (Figure 8b).

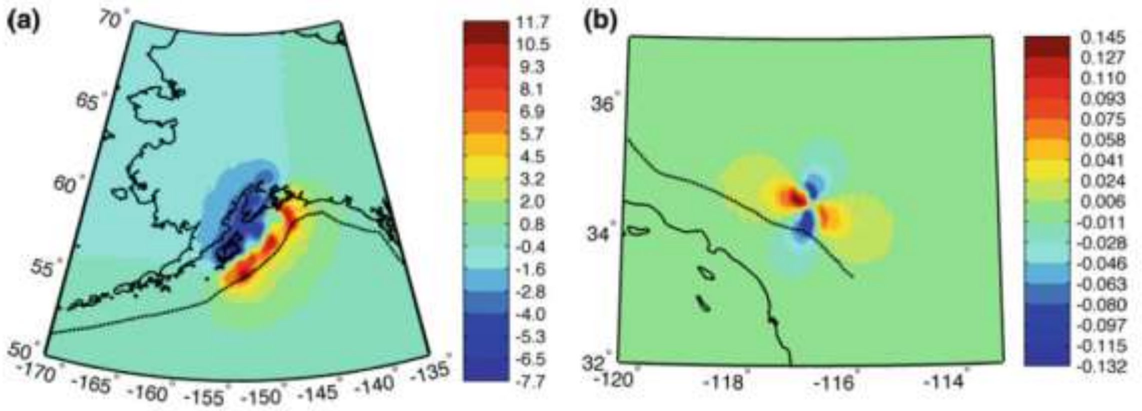

Figure 8: Modeled geoid change in mm for (a) the 1964 Alaska earthquake and (b) the 1992 Landers earthquake. (from Jacob, *et al.,* 2012 – reproduced with permission)

In the event that a large megathrust earthquake (~Mw7.0+) takes place in a geographic area of significance, some form of geodetic response should be employed to assess the magnitude and distribution of geoid change. The exact nature of this response (resolution, observation technique(s), etc.) would need to be arrived at based on the local and specific episodic situation.

3. RELATIONSHIP TO THE NATIONAL SPATIAL REFERENCE SYSTEM (NSRS)

The GeMS derived products have an obvious relationship to other elements within the NSRS especially their corresponding static quantities. At present, let's consider four basic, geopotential related quantities: geoid undulation, surface gravity, surface elevations, and deflections of the vertical. Additionally, a spherical harmonic model for the Earth's external gravitational potential will be the basis for many of these elements both in the static case and the time-dependent case. All of the quantities have a static component, a dynamic component, and a combined model.

1) Spherical harmonic model (SHM) of the Earth's external gravitational potential (GM2022)
    a. Static Geopotential Model of 2022 (SGM2022) – to degree/order 2160.
    b. Dynamic Geopotential Model of 2022 (DGM2022) – to degree/order TBD (likely 180).
2) Geoid Undulation (GEOID2022)
    a. Static Geoid Model of 2022 (SGEOID2022)
    b. Dynamic Geoid Model of 2022 (DGEOID2022)
3) Digital Elevation Model (DEM2022)
    a. Static DEM of 2022 (SDEM2022)
    b. Dynamic DEM of 2022 (DDEM2022)
4) Surface Gravity Model of 2022 (GRAV2022)
    a. Static Gravity model of 2022 (SGRAV2022)
    b. Dynamic Gravity model of 2022 (DGRAV2022)
5) (Surface) Deflection of the Vertical (DoV) model of 2022 (DEFLEC2022)
    a. Static Deflection of the Vertical model of 2022 (SDEFLEC2022)
    b. Dynamic Deflection of the Vertical model of 2022 (DDEFLEC2022)

The four combined quantities (GEOID2022, DEM2022, GRAV2022, and DEFLEC2022) are obtained through a simple addition of the static and dynamic model contributions at the appropriate time epochs as in equation (2) for DEM2022. Each of the individual static and dynamic models will be constructed slightly differently utilizing the spherical harmonic model as a basis and then adding appropriate high frequency information as necessary.

$$DEM2022(\varphi,\lambda,t) = SDEM2022(\varphi,\lambda,t_0) + DDEM2022(\varphi,\lambda,t-t_0) \quad (2)$$

It is slightly less obvious how GM2022 is combined. There are two possibilities: 1) SGM2022 and DGM2022 are combined spectrally at a user desired epoch, or 2) SGM2022 and DGM2022 are individually used to create their respective static and dynamic quantities which are then combined. In the first situation, the GM2022 model at any time epoch could be created on-the-fly in the spectral domain (i.e. GM2022(t) = SGM2022(t_0) + DGM2022(t-t_0)), but it would not be consistent with any of the combined gridded models (like

GEOID2022) at that time epoch. The reason for this discrepancy is the additional information that is added to either the static or the dynamic component grids after synthesizing from the spherical harmonic model. For example, synthesizing the geoid undulation from $c_{nm}(t)/s_{nm}(t)$ would not be equal to the N(t) from SGEOID2022(t_0) + DGEOID2022(t-t_0) as both component models would be augmented with additional information (e.g. addition of high frequency content). This limits the usefulness of a GM2022(t) product. It is likely that NGS would provide users the information and software to do this combination, but the official models would be released and delivered in a gridded format.

4. ANTICIPATED GeMS PRODUCTS, RESOLUTIONS, AND UPDATES

There are a number of geopotential related quantities that need to be provided from GeMS along with how best to release these products. The four main operational products along with a spherical harmonic model of the earth's external gravitational field were specified in Section 3. These five products need to meet a few key practical considerations to be useful in a geodetic reference system. First, all of the products need to be consistent between one another. This consistency is essentially provided by the single spherical harmonic model composed of a static and dynamic component models. Secondly, all of the products need to be defined with backward and forward compatibility through time. This allows a user to either incorporate old data collected in the past into a future survey and vice versa. This must be a consistent path through the models and while it may seem basic, needs to be ensured. Finally, the products must have some practical considerations built into them. Scientifically and mathematically, the models can be developed to capture very complicated temporal frequencies and miniscule magnitudes (~0.01 mm). However, this increases the complexity enormously and some balance needs to be maintained.

As discussed in Section 2, it is evident that a number of complicated time signatures could be included into GeMS products including annual, semi-annual, and even higher terms. For much of the global geodetic community, it is very likely that only a linear time rate of change term would be significant in time-rate of change geoid models. The reason for this is twofold: 1) it is much easier to implement and less confusing for everyone involved, and 2) the annual amplitudes (and additional higher-order terms) are very small and probably not worth incorporating into a model (except in specific geophysical environments and limited geographical areas). Currently, this decision has not been made at NGS and will likely be reevaluated at regular intervals over the long term as geophysical processes change and users become more comfortable with the additional complexity.

On the topic of updates to the model, the NGS Blueprint 2 document (NGS, 2017) specifies that updates to any of the components within NAPGD2022 (GM2022, GEOID2022, DEFLEC2022, and GRAV2022) will lead to a new version for all of the components. In this way, it is perfectly clear that NAPGD2022v05 contains SGEOID2022v05, DGEOID2022v05, etc. In this updating and versioning, the epoch of the static field does not change. Therefore, it would be possible to capture rate changes and episodic events incrementally and then incorporate these changes into the dynamic component models of subsequent versions of NAPGD2022. For example, the hypothetical geoid undulation time series shown in for a given location is incrementally included in three versions of NAPGD2022 all with the same static epoch of t_0 = 2015.0.

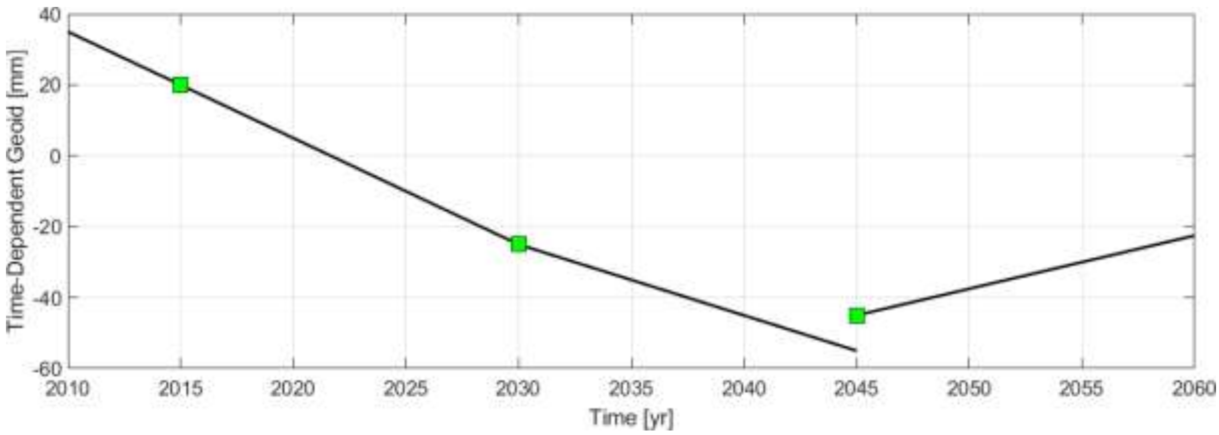

Figure 9: Hypothetical geoid undulation time series with rate changes [mm]. Static geoid epoch = 2015.0.

The first linear trend for time ranges from 2010 to 2030 is incorporated into v01. At some point after 2030 (say 2035), v02 is created which still includes the 2010-2030 time range but now also includes the second linear trend from 2030 to 2045. At some time after 2045 (say 2047), v03 is created which includes all the linear trends from 2010 to 2060 as well as the Heaviside function at 2045 due to an episodic event. In this way, all subsequent iterations are completely backwards consistent to the initial static epoch. The model versions are forward looking (in prediction) until something significant warrants a change to that version's rates.

The initial spatial resolutions of the dynamic models will be set to match the corresponding static model ease of use. For GEOID2022, both SGEOID2022 and DGEOID2022 will likely be 1 arcmin models. DEFLEC2022 has traditionally been a 1 arcmin model and will likely continue to be at that resolution. Both GRAV2022 and DEM2022 will require a higher spatial resolution than 1 arcmin but this is TBD at the current time.

It is completely expected that 'patches' to the various dynamic models will be necessary in order to capture changes in the future. These patches could be defined over a much smaller geographic region (maybe < 1^o) and could be provided at higher spatial resolutions than the original models. In the versioning situation shown in Figure 9, the 'step' feature located at 2045.0 could be included in a locally defined patch where the episodic event is most prominent.

5. CONCLUSION

A dynamic geopotential model (encompassing a number of related components) is one additional piece of the vertical reference system that is likely to be developed by various countries throughout the world in the next decade. With the extremely accurate and long time series of satellite gravity provided by the GRACE mission, geodetic agencies now have the ability to accomplish this. The dynamic geoid signals as shown in a number of previous figures are very small in magnitude (a couple mm/yr) and likely smaller than the observational errors a user would be concerned about. However, these are not random processes that can be removed from positional results through redundant observations. These are systematic effects that if allowed to build up within a geodetic infrastructure lead to appreciable errors.

There are a limited number of geophysical processes that significantly impact the shape of the geoid. These processes must cause mass redistribution of the Earth in order to create geoid shape change. The processes typically act on a particular temporal frequency (secular, cyclical, or episodic) and each of these frequency signatures can be included into a mathematical model of the geoid/geopotential change, as necessary.

At NGS, many of our geopotential related products will incorporate both a static and a dynamic component within NAPGD2022. These include models for the geoid, surface gravity, DEM, and surface DoVs. There are some basic requirements that need to be met for using these models including consistency across all models, consistency going forward or backwards in time, and a balance between practicality and complexity. While out of the scope of this document, some form of external validation needs to be developed to access how well a time dependent geopotential model performs.

REFERENCES

Bevis, M., & Brown, A. (2014). Trajectory models and reference frames for crustal motion geodesy. Journal of Geodesy, 88(3), 283-311.

Fukuda, Y., Kazama, T., Takiguchi, H., Stagpoole, V., O'Brien, G., Caratori Tontini, F. (2018). Gravity changes due to the 2016 Kaikoura earthquake. International Association of Geodesy (IAG) symposium "Gravity, Geoid and Height Systems 2", GGHS 2018. Copenhagen, Denmark.

Jacob, T., Wahr, J., Gross, R., Swenson, S., & Geruo, A. (2012). Estimating geoid height change in North America: past, present and future. Journal of Geodesy, 86(5), 337-358.

Luthcke, S.B., T.J. Sabaka, B.D. Loomis, *et al.* (2013), Antarctica, Greenland and Gulf of Alaska land ice evolution from an iterated GRACE global mascon solution. J. Glac.; 59(216), 613-631, doi:10.3189/2013JoG12J147

McCubbine, J. (2018). Personal communication, October 15, 2018.

Müller, J., Dirkx, D., Kopeikin, S. M., Lion, G., Panet, I., Petit, G., & Visser, P. N. A. M. (2018). High performance clocks and gravity field determination. Space Science Reviews, 214(1), 5.

National Geodetic Survey. (2017). Blueprint for 2022, Part 2: Geopotential Coordinates, NOAA Technical Report NOS NGS 64, available at: https://www.ngs.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0064.pdf

Rangelova, E. (2009), PhD Dissertation. University of Calgary.

Save, H. and the CSR Level-2 Team, "GRACE RL06 Reprocessing and Results from CSR," EGU2018-10697, EGU General Assembly 2018.

Wahr, J., Molenaar, M., & Bryan, F. (1998). Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. Journal of Geophysical Research: Solid Earth, 103(B12), 30205-30229.

BIOGRAPHICAL NOTES

Dr. Ahlgren is the NGS Project Manager for the Geoid Monitoring Service project. He also is involved in numerous geoid related projects at NGS and is an active member of FIG Commission 5.

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