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Exploring and Quantifying the Contribution of Linear Coordinate Functions at NOAA CORS Network Stations to the 2022 Intra-Frame Velocity Model: An Experiment

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“I never allow myself to become discouraged under any circumstances. I recall after we had conducted thousands of experiments on a certain project without solving the problem, one of my associates, after we had conducted the crowning experiment and it had proved a failure, expressed discouragement and disgust over our having failed ‘to find out anything.’ I cheerily assured him that we had learned something. For we had learned for a certainty that the thing couldn’t be done that way, and that we would have to try some other way. We sometimes learn a lot from our failures if we have to put into the effort the best thought and work we are capable of.”

- **Thomas Edison, *The American* Magazine, January 1921**

“Failure is always an option”

- **The Mythbusters**

1 On the need for an Intra-Frame Velocity Model

In 2022, the National Geodetic Survey (NGS) will be modernizing the National Spatial Reference System (NSRS) the official coordinate system for all federal civil agencies, and often adopted by state and local governments. As part of that modernization, a crustal motion model will be developed, predominantly to serve as a statistical estimate of how passive control may have moved between the epochs when it had been surveyed. Such estimates currently exist in NGS's product, Horizontal Time Dependent Positioning (HTDP), however the future crustal motion model (called an Intra-frame velocity model, or IFVM), will differ from HTDP in two ways: it will be in three dimensions (including changes in ellipsoid height) and it will come with formal error estimates of all motions.

The primary purpose of the IFVM will be to assist in performing least-squares adjustments for the purpose of estimating geodetic coordinates at points at epochs different from the epochs at which those points were surveyed. As such, the statistical properties of the IFVM are of the utmost importance. However, attempting to monitor the actual motions of every point on Earth's crust through all years and accounting for all geophysical phenomenon is a monumental task. As such, the IFVM should not (and will not) be treated as a "truth" data set, plotting point movements through time. Rather those motions through time should be seen as what they are: modeled estimates with uncertainties. Their primary function will be as stochastic prior information in a least squares adjustment which takes Final Discrete Coordinates (FDCs, AKA "time dependent coordinates") and attempts to estimate Reference Epoch Coordinates (RECs, AKA "coordinates at one common epoch" such as 2020.0), as per Blueprint for 2022, Part 3 (NGS, 2019). Because of this role, it is critical that the IFVM be free from systematic errors, leaving random errors only.

In 2018, NGS met with industry partners and heard their feedback about the modernized NSRS. One of the primary "asks" was that an early ("alpha") version of every modernized product and service be created years before 2022. As such, NGS set the goal of having alpha versions of everything by the end of 2019. This report reflects an attempt to create an alpha version of the IFVM. However a number of significant difficulties existed when contemplating this task – first, institutional knowledge on the topic of crustal motion has diminished over the last decade. This is one of the reasons HTDP updates have slowed to effectively none. Dedicating in-house resources to collecting geophysical data, and properly incorporating it into a new crustal motion model would mean slow-downs in other key efforts to both ongoing NGS mission functions and/or modernization efforts. In 2019 NGS had begun a collaborative effort with the Scripps Institution of Oceanography (SIO) to study what data and approaches are necessary for the final IFVM, those efforts were nowhere near ready for an alpha version, even in late 2019.

Because the IFVM will serve as input to create Final Discrete Coordinates (FDCs) and Reference Epoch Coordinates (RECs; NGS, 2019), and because alpha versions of those coordinates were on hold until an alpha IFVM was available, some solution needed to be sought. Three came to mind:

1) Wait for the SIO work to complete. This has the advantage of likely being close to the final IFVM, but has the disadvantage of waiting until late 2020 if not into 2021 before even an alpha version is available.
2) Adopt an external model, such as the TRANS4D model (Snay et al, 2016).
3) Create a crude model in house based on immediately available data

This third option had been discussed informally within NGS for years, and sometimes was called simply "gridding CORS". The idea of using just CORS data, without any coseismic data, geodynamic models or SAR based crustal motion monitoring, was controversial to say the least. A CORS is generally built in a location of stability, and therefore even with 2000 of them in CONUS alone, the hope that some significant earthquake signals might be captured was compelling. But the lack of actual physics in such an approach was known to be a weakness, as was the sparseness of stations in most parts of the USA. On the other hand, the GPS data at the NCN was extensive, free and immediately available. At the very least it was felt that the CORS-only contribution to an IFVM should be tested and quantified.

While other groups are working with NGS for incorporating multiple data sources into the best IFVM we can make, this report reflects a simplified version based solely upon data that was immediately on hand at NGS: the velocities and discontinuities at the NOAA CORS Network (NCN) and the IGS Network.

The software to grid these velocities and discontinuities was readily available through a modification of the recently re-created NADCON and VERTCON build software within NGS. Having said that, it was not expected that the grids created in this version of the IFVM would reflect the final IFVM choice in 2022. But there is certainly an elegance and simplicity to this *approach* which NGS will consider.

As such, this study was undertaken solely as an experiment, to gather knowledge first and, secondarily, to see if any sort of reasonable IFVM could be created that might be used when testing the LSA code which would generate RECs.

2 Data: Coordinate functions

NGS uses the term "coordinate function" to mean the *set* of three functions, one each for X, Y and Z (in some particular ITRF), assigned to one particular CORS, which reflect the ITRF coordinates of that CORS through time. Other terms, which mean the same thing as "coordinate function" which are frequently found in the literature are "trajectory" or "solution". While the term "coordinate function" is not in frequent use, it is the mathematically correct term for what it represents: for any given CORS and given one unique time, there should be one unique X, Y and Z value, if a value exists at all, at that time. By definition, this is a "function". Because it reflects the ITRF 2014 coordinates, NGS adopts the term "coordinate function".

An examination of the coordinate functions assigned to all CORSs in the NCN and the IGS Network will show the same general structure for every station:

1) Each function has a begin time (usually the date when the station began collecting data)
2) Each function has an end time (usually the last date when data were allowed to be put into so called "Multi Year CORS solutions" (also called "Reprocessing efforts" or "Repros")
3) In the span between the begin time and end time, each function is made up one or more time-limited functions (called "solutions" in the terminology of the MYCS and in the SINEX files in which the coordinate functions reside).

That is, in general terms, any given station might have solutions which look like this:

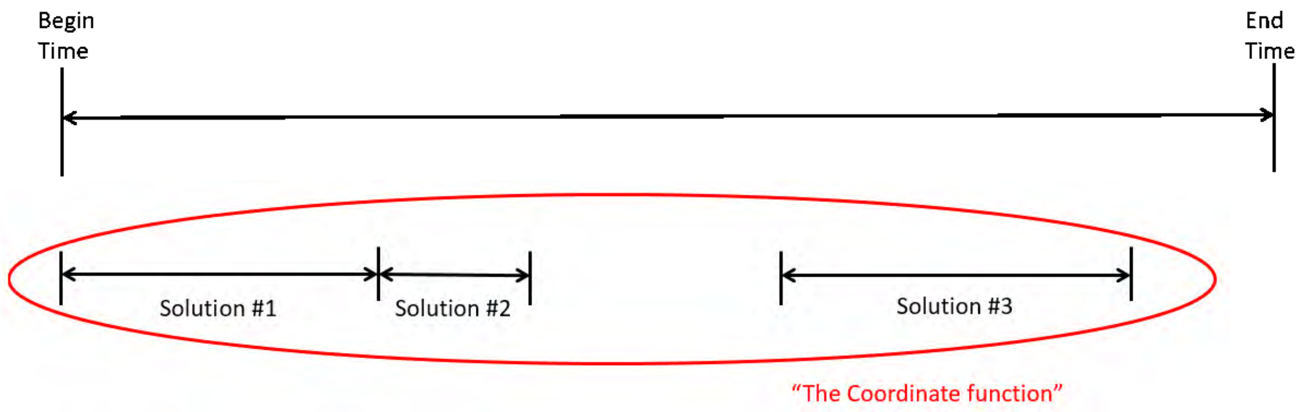

Figure 1: A generic view of how *solutions* might make up a *coordinate function* at a generic CORS

The following rules *should be* applicable to all solutions for any station's coordinate function:

1) Solution numbers and their time spans are identical for X, Y or Z
2) Solutions do not have to begin at "begin time", but they may
3) Solutions cannot begin before "begin time"
4) Solutions do not have to end at "end time", but they may
5) Solutions cannot end after "end time"
6) Solutions do not have to abut one another in time, but they may
7) Solutions cannot overlap with one another in time
8) Each solution is a piecewise continuous function, with continuous derivatives of all orders, consisting of at least a constant term ("coordinate at reference epoch") and first order polynomial ("linear velocity")[1]

At the time of this report, solutions are only built using two terms: the constant term and a velocity. Although NGS is considering other more complicated functions in the future, they will not play a role here.

2.1 The MYCS2 SINEX file

As a first step in developing this alpha product, the preliminary SINEX file (**repro2.snx**) containing all of the solutions for every station was provided on May 17, 2019. It contained all of the solutions for 3049 CORSs between **January 1, 1996 (00:00:00)** ("begin time")[2] and **January 28, 2017 (23:59:59)** ("end time").

A program to analyze this file and provide some basic statistics was run (**ifvm01a.f**). It was fortuitous that this initial analysis was performed, as it pointed out some issues (later traced to an IGS-provided discontinuity file) which broke the above rules. Specifically, the following problems were identified:

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[1] This does not make a coordinate function "piecewise continuous" though. Any non-instantaneous discontinuity between two solutions would make the coordinate function "discontinuous".

[2] Actually, solutions for 61 stations extend back to 1995 and 25 stations extend back to 1994, but NGS is only publishing coordinate functions from 1996 forward for MYCS2.

- Solutions that overlapped (from days and years)
- Solutions that were entirely enveloped in time by another solution
- Solutions with zero durations

This information was fed back to the CORS team, and the sources of error were identified and the most egregious errors were corrected. However one significant source of error still remained, due to an artifact in how the solutions were fit to data.

Specifically, out of 8221 solutions at 3049 CORSs, there were 149 cases of overlapping solutions where the overlap was less than 7 days. This 7 day window is important, because NGS's current workflow takes daily coordinates, averages them into weekly coordinates and then fits the "solutions" to those weekly coordinates. That means discontinuities, which are frequently instantaneous events like Earthquakes, are "smeared" in time over a week, allowing these small overlaps. While this situation is not ideal, it is not particularly troublesome to this study. Nonetheless, ***NGS should consider a different approach in the future which actually bounds "solutions" of coordinate functions by the instantaneous epochs of discontinuities.***

After cleaning up the more egregious errors, these remaining 149 were fixed **solely for this study**, by modifying the start time of the latter of the two overlapping solutions in each of the 149 cases. That start time was modified to be exactly the same as the end time of the earlier solution in the overlap.

Some other interesting statistics of note:

Table 1: Statistics of the MYCS2 SINEX file

Number of CORSs	3049
Total number of solutions	8221
Maximum number of solutions at any CORS	18

A breakdown of how many CORSs had how many solutions is seen in the table below:

Table 2: Solutions per CORS in MYCS2 SINEX file

Number of solutions in the coordinate function	Number of CORSs with this number of solutions	Number of solutions in the coordinate function	Number of CORSs with this number of solutions
1	862	10	9
2	864	11	4
3	578	12	1
4	321	13	2
5	189	14	2
6	119	15	0
7	57	16	0
8	23	17	0
9	17	18	1

The reason for breaking up the coordinate function into multiple "solutions" is, ostensibly, because some observable discontinuity occurs which seems to indicate that the coefficients of the function *before* the discontinuity are different than the coefficients of the function *after* that discontinuity.

3 Basic approach: Drifts and Shifts

Because only linear fits were used in the "solutions", the information content within each station's coordinate function can be summed up as:

1) For the duration of any "solution", the station is moving at a constant velocity in a constant direction
2) When two solutions abut one another in time, but there is a non-zero difference between the functional value of the two solutions at that abutment, then an instantaneous "jump" appears to have happened at that station
3) When two solutions do *not* abut one another, then this causes an information gap between the end of one solution and the beginning of another solution. Such information gaps might be as short as a few seconds or as long as years. Later in the paper these information gaps will be sorted into "brief discontinuities" (treated effectively the same as instantaneous jumps) and "extended discontinuities" (treated as true information gaps).

While the above list is true, it is only a simplistic view of what the data alone can tell us about crustal motion at that station. Further information can be added to the mix. Each will be discussed in the next few sections.

However, before broadening the information content, it should be noted that the above behavior of each coordinate function is the inspiration for how this early version of the IFVM2022 model is being built. Very specifically, a station can be said to "drift along with a constant velocity for a while, until such time as it is interrupted by an instantaneous shift in position, after which it drifts again with constant velocity until interrupted again, etc."

Thus the movement of each station (and by extension the crust to which it is attached) can be said to move in an interwoven set of "drifts and shifts".

Thus will this version of the IFVM be built in a similar manner. A series of "drift grids" (grids of constant velocity occurring between some start epoch and some stop epoch) and "shift grids" (grids of instantaneous movements at some specific epoch) will be built, based upon the coordinate functions as well as additional information, as explained in the next sections.

3.1 Identifying earthquakes to "keep"

As noted earlier, only 862 CORSs have a single solution as part of their coordinate function. That means discontinuities occur in the coordinate functions of 2187 of the 3049 CORSs. In the most extreme case (station AB36) 18 solutions spread over only 10 years (2007-2017) imply that 17 discontinuities occur in that 10 year period. It would be useful to sort *brief* discontinuities from *extended* discontinuities, (since "brief" discontinuities, if "brief enough" might be considered effectively the same as an instantaneous jump) and *especially* useful to know which brief discontinuities can be attributed to actual nearly-instantaneous movement of the station from some real physical force, such as an earthquake. This is no simple task, but it was not impossible either. A number of barriers to success needed to be overcome, as described below.

The first barrier is that, unfortunately, there is a difference between the coordinate function and the actual location of the station on Earth. Specifically:

> **Coordinate Function:** A series of solutions (currently sloped lines) fit by NGS to the daily or weekly ITRF coordinates computed by NGS from data recorded by the equipment at the station.
>
> **Actual location:** The actual ITRF XYZ coordinates of the Geometric Reference Point (GRP) at each station at any given time.

The GRP is a concept long understood, but heretofore poorly implemented at NGS and other agencies. It is a unique, zero-dimensional permanent physically identifiable point located somewhere on the station, and independent of any electronic equipment that may or may not be mounted at the station.

This splitting of hairs is critical to make a point: the daily/weekly computed coordinates are well known to have discontinuities that are unrelated to any actual physical movement of the station itself. The two most common pieces of metadata which are associated with such discontinuities are "equipment change" and "unknown".

An equipment change might mean changing the pre-amp in an antenna, replacing the antenna itself, replacing some other piece of electronics or other change which does not change the monument at the station. That is, there is no reason to believe the actual location of the station (the GRP specifically) moved. These discontinuities come from an inherent weakness in GNSS itself: despite the invention of "absolute antenna calibrations" in the early 2000s, such calibrations take place in an environment that is different than the environment in which the antenna itself is actually mounted. And since performing absolute antenna calibrations currently requires the use of bulky, expensive robotic contraptions, it is not currently possible to perform in-situ absolute antenna calibrations.

There is not much that can be done about cause-unknown jumps in daily/weekly coordinates, as they can come from true motion, unrecorded equipment changes or some other unknown source.

From this point on, the term "earthquake discontinuity" will be applied to brief discontinuities which were (in this study) attributed to an earthquake, while "spurious discontinuity" will be applied to a brief discontinuity which cannot be directly attributed to an earthquake. As NGS is not the official arbiter of earthquakes, the first step in sorting them out was to acquire an earthquake list. For that, we turned to the USGS earthquake website (https://earthquake.usgs.gov/earthquakes/search/).

Such a list could be more extensive than necessary, so the following bounds were made:

1) January 1, 1996 through January 28, 2017 (dates which bound coordinate functions in the MYCS2)
2) Magnitude 6 or higher
3) Within 5 arcdegrees of the 6 major regions in which the IFVM2022 model will be valid

The six major regions of IFVM2022 are identical to those used in **NADCON 5.0 release 20160901** (Smith and Bilich, 2016). Their boundaries, the boundaries of the earthquake search and the number of earthquakes found are shown below.

Table 3: Six regions of the IFVM

Region	Boundaries				Earthquake search				Number of Earthquakes Found
	N	S	W	E	N	S	W	E	
CONUS	50	24	235	294	55	19	230	299	47
Alaska	73	50	172	232	78	45	167	237	146
Hawaii	23	18	199	206	28	13	194	211	2
PR/VI	19	17	291	296	24	12	286	301	9
Guam/CNMI	22	12	143	147	27	7	138	152	65
Am. Samoa	-13	-16	188	193	-8	-21	183	198	108

NGS has no plans to model intra-frame velocities outside of the boundaries listed in the above table.

The search distance of 5 arcdegrees was an overly conservative estimate designed to collect up every possible earthquake which might impact the actual region in which the IFVM will be created. According to the University of Nevada, Reno (http://geodesy.unr.edu/NGLStationPages/stations/CH01.sta, for example), one could expect a discontinuity within a radius of:

$$R = 10^{\left(\frac{M}{2} - 0.8\right)}\ km \quad (1)$$

where M is the magnitude. It was expected that 9.0 Mw earthquake at most would appear in this search, which would necessitate a search radius of about 5000 km, or about 5 arc degrees at the equator. As it turned out, the largest earthquake found in this search had a magnitude of 8.1 (which would imply a potential discontinuity at stations no further than 1800 km). As such, it was felt that this 5 arcdegree search buffer was more than adequate.
Even so limited, the list of earthquakes was extensive, as evidenced by the numbers in the above table.

The next question to answer was this: did each of these Earthquakes cause an observable change to one or more CORSs? If so, then a "shift" grid would be justifiable. Creating, for example, 146 "shift" grids for Alaska, with a separate "drift" grid in-between each of them, seemed not only daunting but possibly unreasonable. However, a number of things pointed to the situation being less bleak than that. The first is simply the location of the earthquakes. See the maps below, and note how few of the earthquakes actually are "near" any CORSs. For instance, the supermajority of earthquakes in Alaska are in the Aleutians, a chain of islands with few CORSs and even fewer that pre-date the year 2010. Since earthquakes (as a rule of thumb) tend to move stations nearest to them the most, if there are no stations in the Aleutians to "feel" an earthquake, no data exists[3] and no shift grid can be created.

[3] This seems like an appropriate time to put out a reminder: this study is based solely upon NCN and IGS Network station data. External sources of data, such as fault models and InSAR-based crustal changes are not being used. Without stations near an earthquake, no information about the earthquake is available. Basically "if a tree falls in the forest, and nobody is around to hear it, did it make a noise?" becomes "if an earthquake happens and no CORSs are around to register it, did the crust move?" (Answer: of course it moved, but to our data-driven approach, no shift grid can be created under these circumstances).

Figure 2: 47 Earthquakes of magnitude 6 or higher within 5 arcdegrees of region "CONUS" between Jan 1 1996 and Jan 28 2017

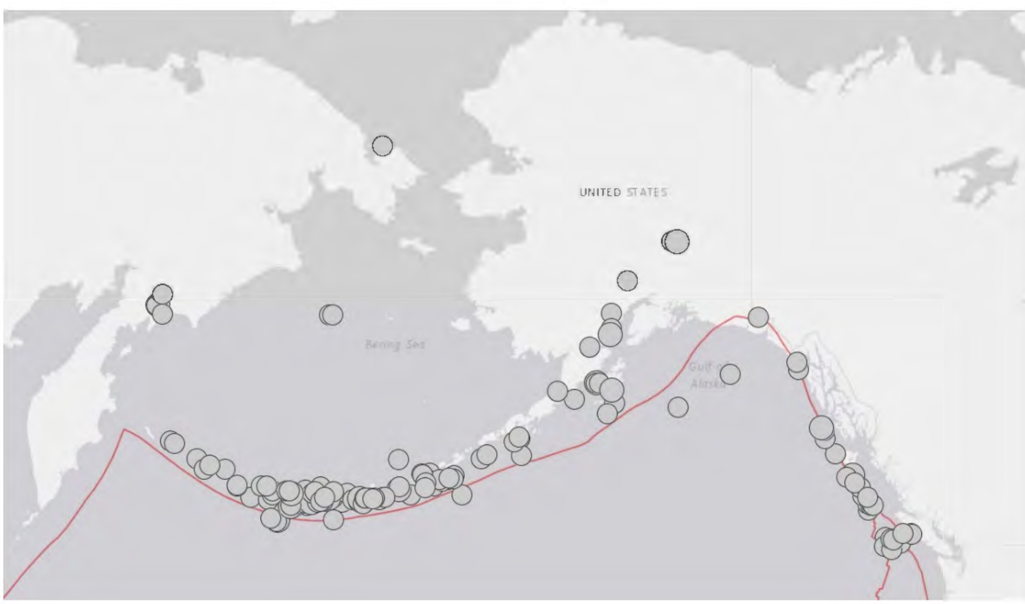


Figure 3: 146 Earthquakes of magnitude 6 or higher within 5 arcdegrees of region "Alaska" between Jan 1 1996 and Jan 28 2017

Figure 4: 2 Earthquakes of magnitude 6 or higher within 5 arcdegrees of region "Hawaii" between Jan 1 1996 and Jan 28 2017

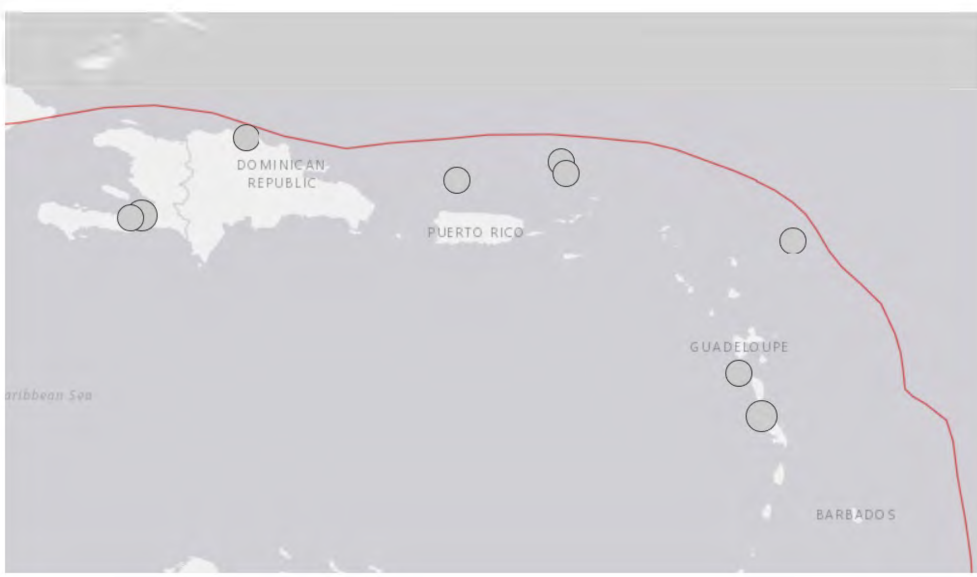


Figure 5: 9 Earthquakes of magnitude 6 or higher within 5 arcdegrees of region "PR/VI" between Jan 1 1996 and Jan 28 2017

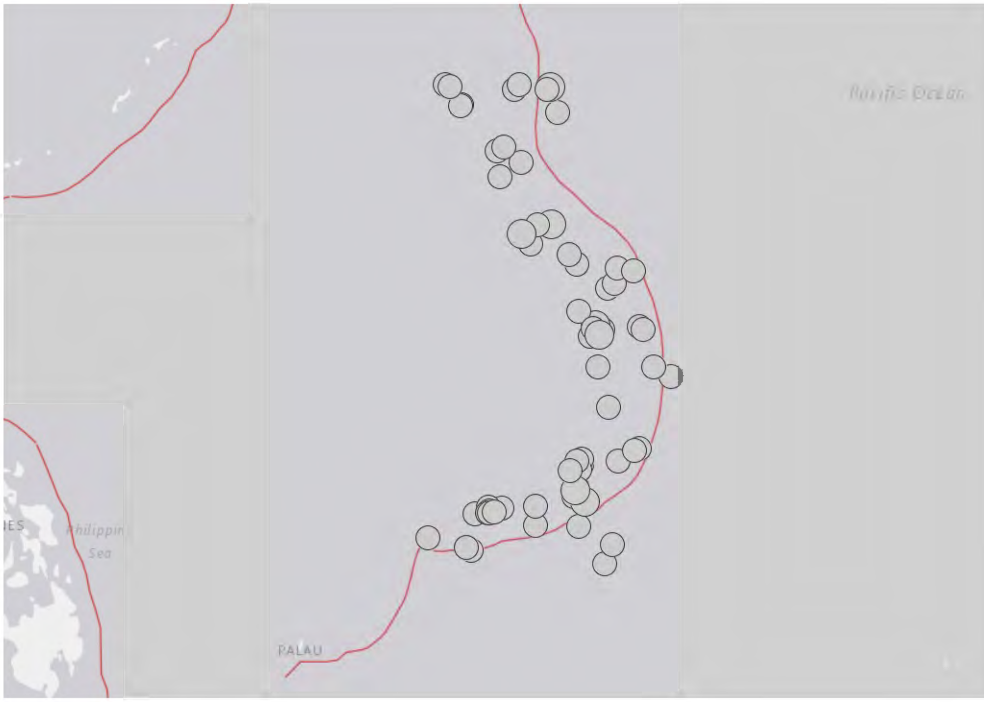


Figure 6: 65 Earthquakes of magnitude 6 or higher within 5 arcdegrees of region "Guam/CNMI" between Jan 1 1996 and Jan 28 2017

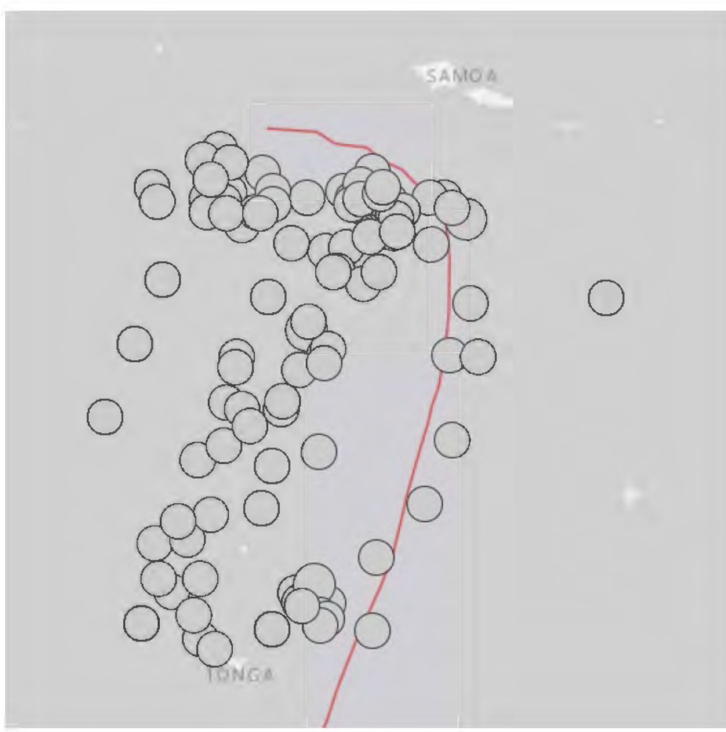


Figure 7: 108 Earthquakes of magnitude 6 or higher within 5 arcdegrees of region "American Samoa" between Jan 1 1996 and Jan 28 2017

The above figures and the numbers in Table 3 just for earthquakes. An identical search (but with minimum magnitudes dropped to 2.5) performed on the USGS website for *other* (non-earthquake) events (with a particular interest in **volcanic activity**) yielded zero results for all six regions. This seems unreasonable, considering known volcanic activity in the Guam/CNMI region (Pagan 2006, 2009, 2010, 2011; Anatahan 2003, 2005) and Hawaii (2014). Future work should properly identify volcanic activity and add it to the mix, but for the sake of expediency, this was not pursued for this study.

With the official list of solutions at all CORSs from MYCS2, and an official list of earthquakes against which to compare them, a computer program (**mkinfiles.f**) was written and run with the express purpose of sorting "brief discontinuities" from "extended discontinuities", and attempting to correlate earthquakes with brief discontinuities. [4]The logic went as follows (performed for each of the six regions separately):

1) For a given CORS, the end time of one solution and the beginning time of its next solution were compared. If the time between the two was less than 1 month, then this was labeled as a "brief discontinuity". If longer than 1 month, this was labeled as an "extended discontinuity"
2) For every CORS that was in existence during an earthquake, and not in the midst of an "extended discontinuity", an attempt was made to see if a brief discontinuity in this CORS's coordinate function was associated with the earthquake:
    a. For every "brief discontinuity", if one of the two endpoints (either the end time of the earlier solution or the start time of the latter solution) fell within 7 days of an earthquake, then this brief discontinuity was considered to be associated with this earthquake, and thus the station was considered "affected by the earthquake". The shift was computed and statistics were accumulated.
    b. For those stations which did not have a brief discontinuity at the time of the earthquake, no shift was computed. The station was labeled as "unaffected by the earthquake", and it was added to a running tally of such unaffected stations.
3) All statistics and running counts of "affected" and "unaffected" stations were maintained in rings of ever-increasing radii (50, 100, 200, 400, 600, 800, 1000, 2000, 5000 and 10000 km) around the epicenter of the earthquake.

With this information in hand, a decision had to be made about whether an earthquake had moved "enough CORSs" to justify building a shift grid. Many different definitions of "enough CORSs" were considered, beginning with "just 1 station, at any distance" to more and more complex definitions. The final choice was this:

> ***An earthquake was "kept" (considered to have moved "enough CORSs" to justify creating a shift grid) if, for any ring around the epicenter up to 400 km (800 for Alaska), more CORSs moved than did not move, and at least 3 CORSs (1 for Guam/CNMI or American Samoa) were so moved in that ring. As an additional criteria, any earthquake which moved even 1 CORS (within 400 km, or 800 km in Alaska) by 10 cm or more was also kept.***

[4] After this study was completed, it was pointed out (J. Saleh, personal communication) that a discontinuity file, with attributed causes, was available but was not in the SINEX file upon which this study was performed. For future work, it would be interesting to see how that file agrees and disagrees with the blind search performed herein.

Furthermore, if two or more earthquakes occurred within a week of one another, and more than one fulfilled the above criteria, then the group was treated as one earthquake, at the time of the largest magnitude quake.

It should be pointed out that there is the possibility of a discontinuity occurring around the time of an earthquake that is not caused by the earthquake. While possible, it would be unlikely that multiple such occurrences happened on multiple stations coincidentally near the time of an earthquake. Because of the "kept" criteria (discussed below), such an occurrence would not likely change things, but it would falsely put a "shift" at that CORS. This is a good example of a flaw in this overly blind system, reliant solely upon statistical algorithms and not additional metadata.

As it turns out, these criteria cut most earthquakes off of the "kept" list. Using just this criteria, a list of potential "kept" earthquakes was developed. They are listed in the table below. The reason this is "potential" is that the criteria leave a few earthquakes as "kept" which fall into a gray area. In order to help in their discussion, highlighting appears on the next table. "Highly convincing" evidence is highlighted in green. "Mildly convincing" evidence is highlighted in yellow. The entries in red in the below table represent information outside of the expected radius of influence of the earthquake, based on its magnitude (see equation 1.) Discussion of the table follows it.

Table 4: Potential Earthquakes for Shift Grids

Region	Date (*Name*)	Mw	General Location	Lat/Lon	50 km	100 km	200 km	400 km	600 km	800 km
CONUS	1999.79016 (*Hector Mine*)	7.1	16km SW of Ludlow, CA	34.6 243.7	No CORS	1 moved 2.3 cm	21 moved 1.1 cm ave	9 moved 0.4 cm ave	1 moved 0.8 cm	0 moved
					No CORS	1 didn't move	0 didn't move	8 didn't move	10 didn't move	13 didn't move
CONUS	2005.45238 (*Anza*)	7.2	Off the coast of Northern California	41.3 234.0	No CORS	No CORS	3 moved 1.2 cm ave	1 moved 0.3 cm	0 moved	0 moved
					No CORS	No CORS	2 didn't move	5 didn't move	31 didn't move	44 didn't move
CONUS	2010.02471 (*2010 Eureka*)	6.5	Offshore Northern California	40.7 235.3	4 moved 1.1 cm ave	3 moved 0.5 cm ave	0 moved	1 moved 0.6 cm	1 moved 0.4 cm	1 moved 0.8 cm
					0 didn't move	4 didn't move	13 didn't move	53 didn't move	61 didn't move	81 didn't move

CONUS	2010.25738 (*Baja*)	7.2	12km SW of Delta, B.C., MX	32.3 244.7	No CORS	1 moved 8.3 cm	16 moved 1.4 cm ave	33 moved 0.5 cm ave	3 moved 0.1 cm ave	9 moved 0.2 cm ave
					No CORS	0 didn't move	0 didn't move	34 didn't move	51 didn't move	47 didn't move
CONUS	2014.18691 (*2014 Eureka*)	6.8	78km WNW of Ferndale, California	40.8 234.9	No CORS	8 moved 1.4 cm ave	3 moved 1.0 cm ave	1 moved 0.4 cm	0 moved	0 moved
					No CORS	0 didn't move	11 didn't move	54 didn't move	66 didn't move	89 didn't move
Alaska	2002.8408 *(Denali)*	7.9	Denali national park	63.5 212.1	No CORS	No CORS	2 moved 8.6 cm ave	1 moved 2.4 cm	No CORS	3 moved 0.6 cm ave
					No CORS	No CORS	0 didn't move	0 didn't move	No CORS	1 didn't move
Alaska	2013.01198 (*SE Alaska*)	7.5	S.E. Alaska	55.5 225.1	No CORS	No CORS	No CORS	4 moved 0.8 cm ave	0 moved	1 moved 0.4 cm
					No CORS	No CORS	No CORS	1 didn't move	2 didn't move	3 didn't move
Hawaii	2006.78826 (*Kiholo Bay*)	6.7	Hawaii Region	19.9 204.1	1 moved 1.1 cm	2 moved 1.3 cm ave	2 moved 0.8 cm ave	0 moved	0 moved	No CORS
					1 didn't move	2 didn't move	0 didn't move	2 didn't move	3 didn't move	No CORS
Guam/ CNMI	2002.31691 (*Guam*)	7.1	Guam region	13.1 144.6	No CORS	1 moved 2.0 cm	No CORS	0 moved	No CORS	No CORS
					No CORS	0 didn't move	No CORS	1 didn't move	No CORS	No CORS

Before discussing which of the earthquakes on the above table were actually kept in this version of the IFVM, a few notes should be made about some omissions in the above table:

1) Missing Alaska earthquake, 2002.85105, Mw 6.6 @ 51.2/179.3 (Aleutians): No stations exist within 1000 km of this epicenter. However 2 stations between 1000 and 2000 km moved (0.4 cm ave) ***and 5 stations between 2000 km and 5000 km moved (4.2 cm ave, with 10.2 cm max)***. Considering the distance from the epicenter and the magnitude (which would set a maximum expected discontinuity radius of about 300 km), it would be too much of a stretch to associate these brief discontinuities with this earthquake, and therefore this earthquake was not "kept" in this version of the IFVM.
2) ***The September 29, 2009 (2009.7452) 8.1 magnitude earthquake in American Samoa***, despite completely invalidating all of the heights in the ASVD 02 vertical datum from that date forward, occurred at a time when no CORS has a coordinate function. Strangely, both of the CORS in that region (ASPA and FALE(IGS)) were active and had coordinate functions for the August 30, 2009 earthquake just a month earlier, but by September 29th, no coordinate function exists for either. By the November 23rd earthquake however, FALE was back up with a coordinate function (ASPA followed later in 2010). What this means is that, for this study, the choice of "1 month" as the split between "brief discontinuity" and "extended discontinuity" is preventing a brief discontinuity from being assigned to any CORSs during that big earthquake. Therefore, with no "brief discontinuities" associated with this earthquake, it was not kept in this version of the IFVM.
3) ***No earthquakes in the PR/VI region have any brief discontinuities associated with any stations in the NCN or IGS Network.***

As to the data in the table itself, most of it has evidence which points to the need to keep an earthquake in the IFVM. But a few require some additional scrutiny.

First, the 7.2 Mw in CONUS on 2005.45238 moved 4 of 11 CORSs within 400 km, and 0 of 75 between 400 and 800 km. With an expected discontinuity radius of 630 km (equation 1), this is pretty slim pickings for creating a crustal movement model. Second, the earthquakes for Hawaii and Guam/CNMI in the above table contain very little data as well. This is understandable considering the sparsity of stations in those two regions. In the interest of learning more about how data-starved earthquake models will impact a data-driven IFVM, these earthquakes have been retained on the "kept list".

<u>Therefore it is concluded that the list of earthquakes in the above table is the definitive list of earthquakes in this version of the IFVM.</u>

Finally, a curious observation was made regarding the magnitude of earthquake-associated CORS movements. Assuming a station was in operation more-or-less during an earthquake (that is, it didn't have a 30+ day "extended discontinuity" which straddled the earthquake), the maximum discontinuity (movement) caused to any CORS for any earthquake since 1996 was <u>10.2 cm</u> caused by the 7.9 Mw earthquake on November 3, 2002 in central Alaska to a station within 200 km of the epicenter. Considering that the movement of one road (the Tok Cut-Off) was reported at 7 meters (https://www.fhwa.dot.gov/publications/publicroads/03nov/05.cfm), from this same earthquake, it is surprising[5] that the maximum offset in the entire discontinuity data set so small (70 times smaller than a directly measured crustal offset). Without further investigation, one can only speculate as to what this might mean. For instance, does it mean that CORSs as a whole are purposefully constructed far from faults? Does it mean that earthquakes disrupt electronics for so long that "extended discontinuities" occur from

[5] Surprising to the author. Others at NGS were certain that most CORSs were built in places of expected stability and thus should not be expected to have large shifts. Live and learn.

them, rather than "brief discontinuities"? Does it mean that earthquake-based crustal movement falls off so rapidly as a function of distance from epicenter that CORS density can *never* capture it?

In any case, it is clear that *with the data at hand*, the idea of "gridding CORS" for the purpose of tracking crustal velocities does not seem to contain the amount of information necessary to adequately describe all movements**.** Nonetheless, this study was seen to its end, if for no other reason than to document the knowledge gained, and document the abilities *and* inabilities of "gridding CORS" to adequately capture crustal movement (see quotes at the beginning of this TM). With Mr. Edison and the Mythbusters as companions this project has embraced the potential to end not in "failure" per se, but in "successful knowledge gained."

A pair of computer programs, **mkinfiles.f** and **mkinfiles2.f** were used to analyze the SINEX file and create the input data to the IFVM build software.

3.2 Extending velocities

The number of CORSs in the NCN and IGS Network has obviously grown through the years. The "begin time" for the MYCS2 solution is January 1, 1996. Of the 3048 CORSs in the MYCS2 project, **only 161** actually existed in 1996, *in the entire world*. Many of those stations are outside of the USA, and of those in the USA many are coast guard sites with two stations on the same site. This does not bode well for the idea of capturing crustal motion solely from these stations.

The approach taken in this report is simple: **In the absence of other information, assume that the velocity computed at a station is constant, but allow for the possibility that such a velocity is interrupted by jumps at discontinuities (more on that later).**

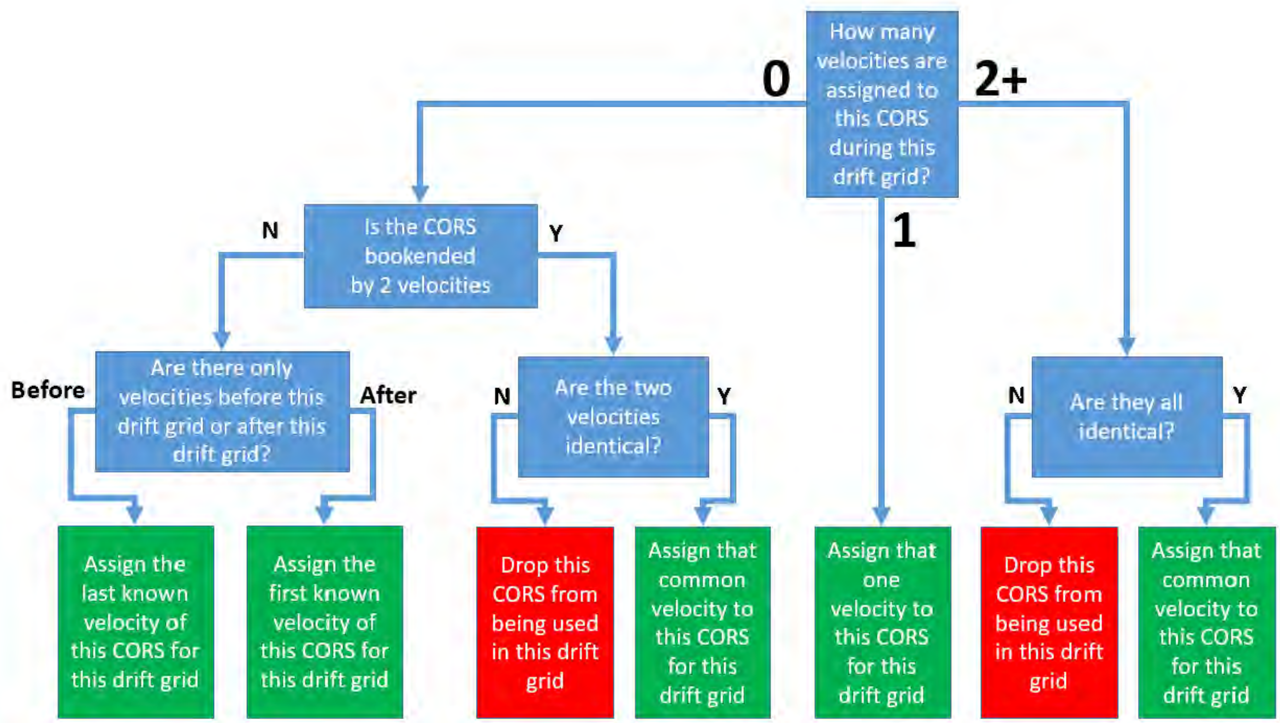
Is this reasonable? The answer initially seemed to be "yes", for a few reasons. First, without any such assumption, the sparseness of CORSs in the late 1990s and early 2000s would mean a data-driven approach would be increasingly starved for data. Second, the standard practice at NGS has been to assume that the general linear velocity of a station tends to remain constant, absent a significant geophysical reason for it to change. This does not mean that velocities are *forced* to be identical in each "solution" for a CORS, but it does mean that there are certain times wherein NGS *will* enforce such a condition.

With the choice of "kept" earthquakes having been made (see previous section), and the choice to build the IFVM as a collated set of "drift grids" and "shift grids", the time spans for each "drift grid" are known. The first one always begins with Jan 1, 1996 and goes to the epoch of the first kept earthquake. That earthquake will mark the time of the first "shift grid". The next drift grid will run from the time of the first shift grid until the time of the next shift grid (kept earthquake #2). This will continue until the last drift grid runs from the last kept earthquake until January 28, 2017.

With this in mind, the following rules were applied, in order to expand the coordinate functions of all CORSs back to "begin time" and forward to "end time", so that their velocities could be included in more drift grids than the station actually operated during. The basic rule of thumb was this: if there is evidence of a change in velocity at a station during a drift grid, drop that CORS[6]. Otherwise, use whatever constant velocity

[6] This means that stations which are known, or expected or even suspected of having a *changing* velocity over the course of a drift grid's duration, will be dropped. Future studies, and in fact future work in general by NGS, should address non-linear velocities, including the possibility of predicting them over times when data are missing at a station.

makes sense based on the data at hand. This is summed up in the next figure, which was applied for any given drift grid timespan for each CORS:



The above logic was contained in "mkinfiles2.f", which also outputs the statistics of this flowchart for drift grids. Those are expressed below.

Table 5: Extending velocities for CORS when they had no data

Region	Drift Start[7]	Drift End	CORSs with constant velocity either existing in this timespan or through bookending	CORSs with 2 or more different velocities in this timespan (dropped)	CORSs with an extrapolated velocity	CORS with 2 different bookended velocities (dropped)
CONUS	1994.00000	1999.79016	209	34	2123	0
CONUS	1999.79016	2005.45238	723	51	1592	0
CONUS	2005.45238	2010.02471	1659	46	661	0
CONUS	2010.02471	2010.25738	1453	49	852	12
CONUS	2010.25738	2014.18691	1847	114	404	1
CONUS	2014.18691	2020.00000	1824	32	510	0
Alaska	1994.00000	2002.84089	20	8	129	0
Alaska	2002.84089	2013.01198	97	51	9	0

[7] 1994.00000 and 2020.00000 were used as arbitrarily set extrapolated IFVM dates. The only actual data used ranges from 1996.00000 to mid 2017.

Alaska	2013.01198	2020.00000	97	33	27	0
Hawaii	1994.00000	2006.78826	12	2	8	0
Hawaii	2006.78826	2020.00000	20	1	1	0
PR/VI	1994.00000	2020.00000	26	1	0	0
Am. Samoa	1994.00000	2020.00000	1	2	0	0
Guam/CNMI	1994.00000	2002.31691	1	1	2	0
Guam/CNMI	2002.31691	2020.00000	3	1	0	0

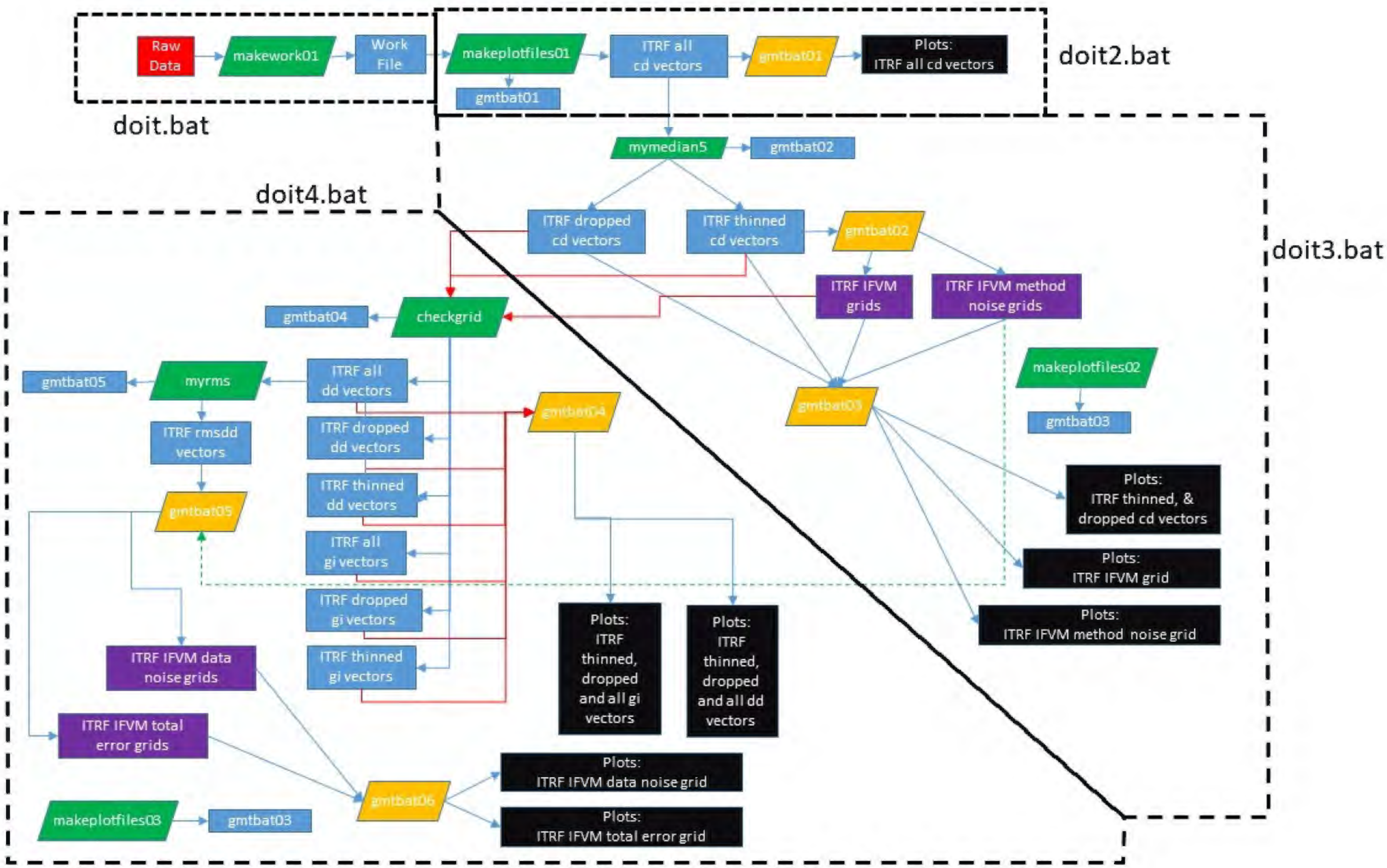
Take special note of the "CORS with extrapolated velocity" values. Without this extrapolation hundreds, and in the earliest cases, thousands, of CORS velocities would not be able to feed the data driven IFVM in CONUS.

At this point, all of the information that might be squeezed out of the CORS-only datasets is in place, and the creation of the shift and drift grids can commence.

4 IFVM2022 v0.01 build 20191107

A suite of build software was generated to turn velocities and jumps into drift grids and shift grids. It so happens that a set of "build software" capable of performing very similar work already existed in the form of **NADCON v5.01** (Smith and Bilich, 2019). With a few weeks of software tweaking, following the same basic flowchart, a new suite of build software, called "**IFVM2022 v0.01**" was created. That build software consisted (as in NADCON v5.01) of four scripts (doit.bat, doit2.bat, doit3.bat and doit4.bat, each building upon the output of the script before it).

A flowchart of data flow through the build software is seen below. The "Raw Data" is in the form of so-called "In Files", created through the aforementioned program "**mkinfiles2.f**". Once those are created, a script called "**makecontrol.bat**" creates a series of "control files". These, with the In Files, are input to the first script, "doit.bat".



doit.bat
Raw Data
makework01
Work File
doit2.bat
makeplotfiles01
gmtbat01
ITRF all cd vectors
gmtbat01
Plots: ITRF all cd vectors
doit3.bat
mymedian5
gmtbat02
ITRF dropped cd vectors
ITRF thinned cd vectors
gmtbat02
ITRF IFVM grids
ITRF IFVM method noise grids
makeplotfiles02
gmtbat03
gmtbat03
Plots: ITRF thinned, & dropped cd vectors
Plots: ITRF IFVM grid
Plots: ITRF IFVM method noise grid
doit4.bat
checkgrid
gmtbat04
myrms
gmtbat05
ITRF all dd vectors
ITRF dropped dd vectors
ITRF thinned dd vectors
ITRF all gi vectors
ITRF dropped gi vectors
ITRF thinned gi vectors
gmtbat04
ITRF rmsdd vectors
gmtbat05
Plots: ITRF thinned, dropped and all gi vectors
Plots: ITRF thinned, dropped and all dd vectors
ITRF IFVM data noise grids
ITRF IFVM total error grids
gmtbat06
Plots: ITRF IFVM data noise grid
Plots: ITRF IFVM total error grid
makeplotfiles03
gmtbat03

Unlike NADCON v5.01 and VERTCON v3.0 build software, this suite did not rely upon "chronologically adjacent datum names" as input. Rather 10 character epochs were used. When two different epochs were fed to the software, it knew to create a drift grid spanning between those two epochs. When the same epoch was fed to the software twice, it knew to create a shift grid at that one epoch. By way of example,

```
doit.bat 1994.00000 1999.79016 conus
```

was the first (of four) commands issued to create the **drift grids** from 1994.00000 to 1999.79016 in CONUS whereas

```
doit.bat 1999.79016 1999.79016 conus
```

was the first (of four) commands issued to create the **shift grids** at 1999.79016.

A comprehensive overview of how the programs inside of each "doit" script can be found in the NADCON v5.0 report (Smith and Bilich, 2017) and will not be repeated here. However a brief overview is relevant:

"doit.bat" creates a "work file", in a specific format, from the In Files and the Control files. It applies deletions to errors that were manually detected in the data (through the course of investigations).

"doit2.bat" plots all of the data from the work file.

"doit3.bat" thins the data into a block-median (user must select a block size), grids the thinned data, and plots both the raw data points (all, thinned and dropped) and the grid itself. In NADCON this would be the "transformation grid", but in this case it is either a "drift grid" (in meters/year) or a shift grid (in meters). It also changes the "tension" of the gridding algorithm in order to gauge its impact on the grid. This tension changing impact is called "method noise".

"doit4.bat" compares all of the data from the work file against the grid, and generates statistics about how, within each block, the original data deviates from the grid. This is called "data noise", and combined with the previous "method noise" is used to create the "error grid". In addition to the error grid, plots of vectors that led to the "data noise", and plots of the error grid itself are created.

4.1 Some example plots for a drift grid

For the first drift grid in CONUS, some relevant plots are:

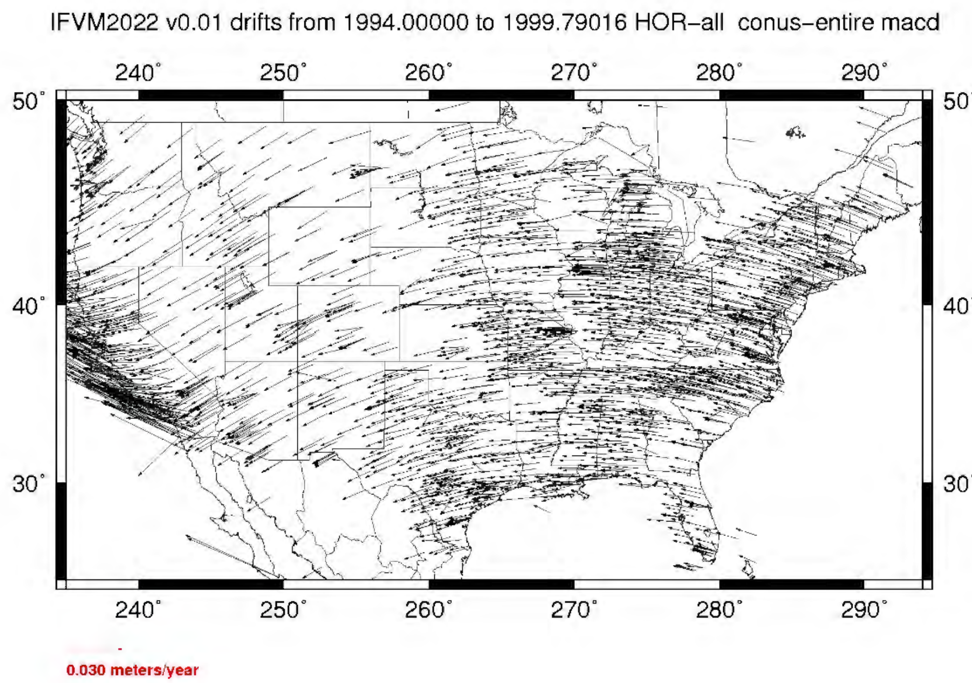


Figure 8: Horizontal DRIFTS

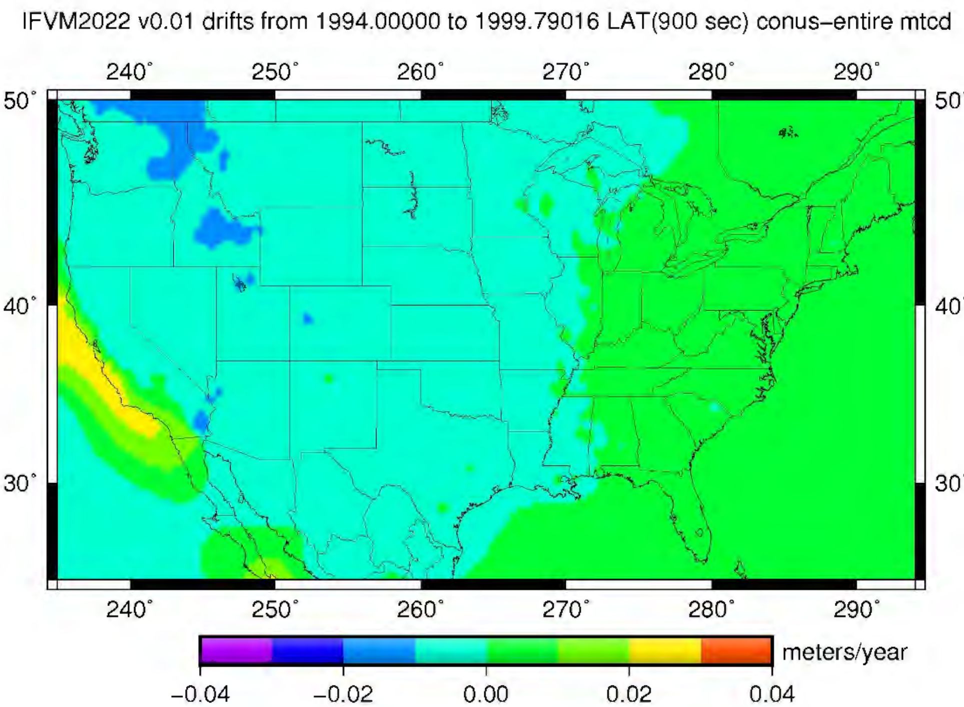


Figure 9: DRIFTS in latitude only (m/y)

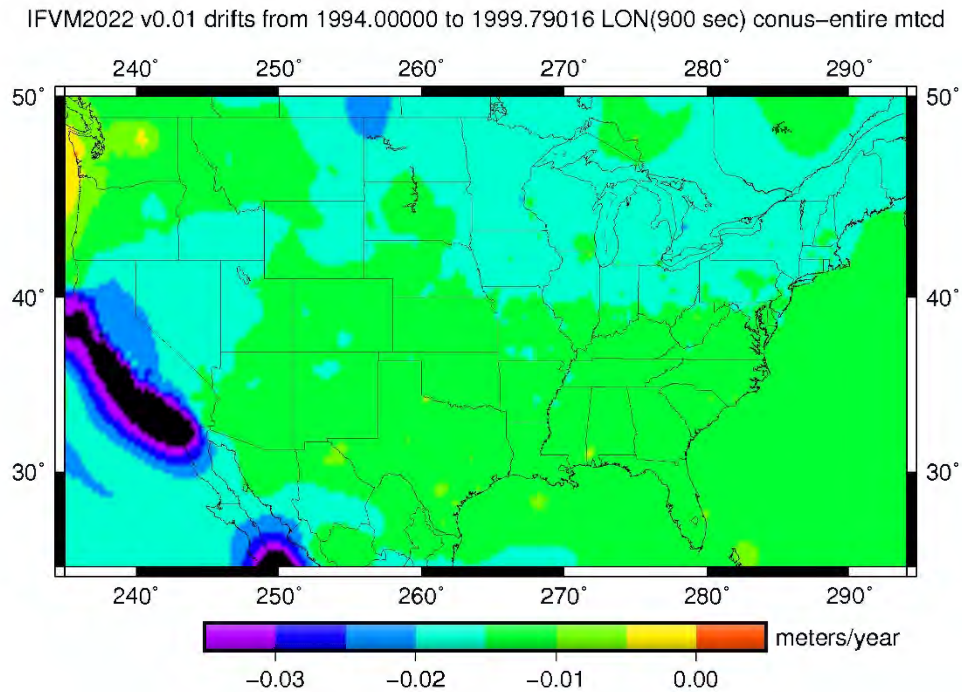


Figure 10: DRIFTS in longitude only (m/y)

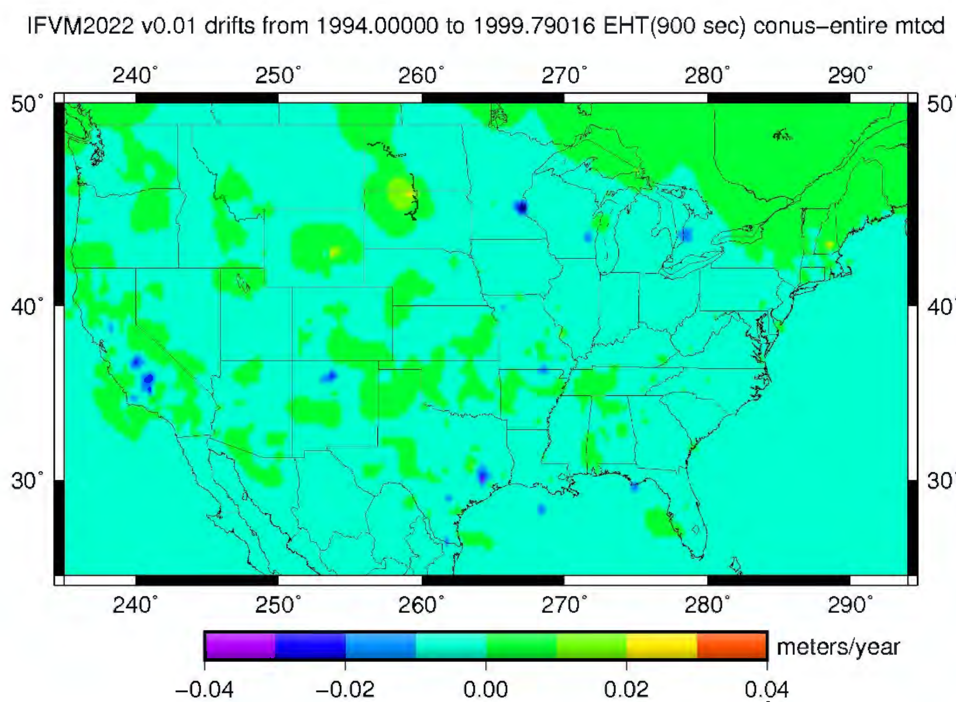


Figure 11: DRIFTS in ellipsoid height only (m/y)

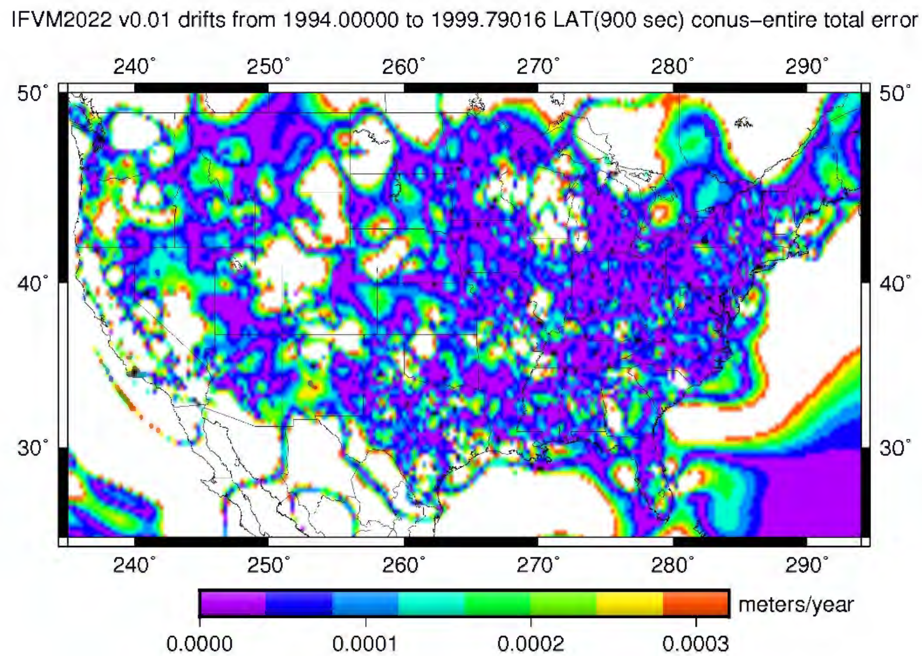


Figure 12: Uncertainties in latitude DRIFT (m/y)

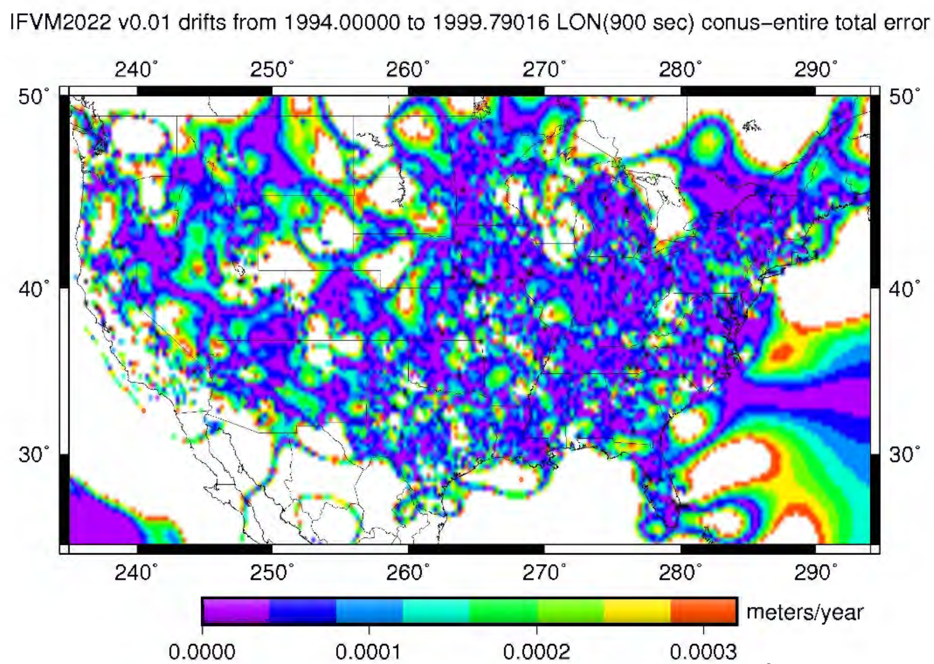


Figure 13: Uncertainties in longitude DRIFT (m/y)

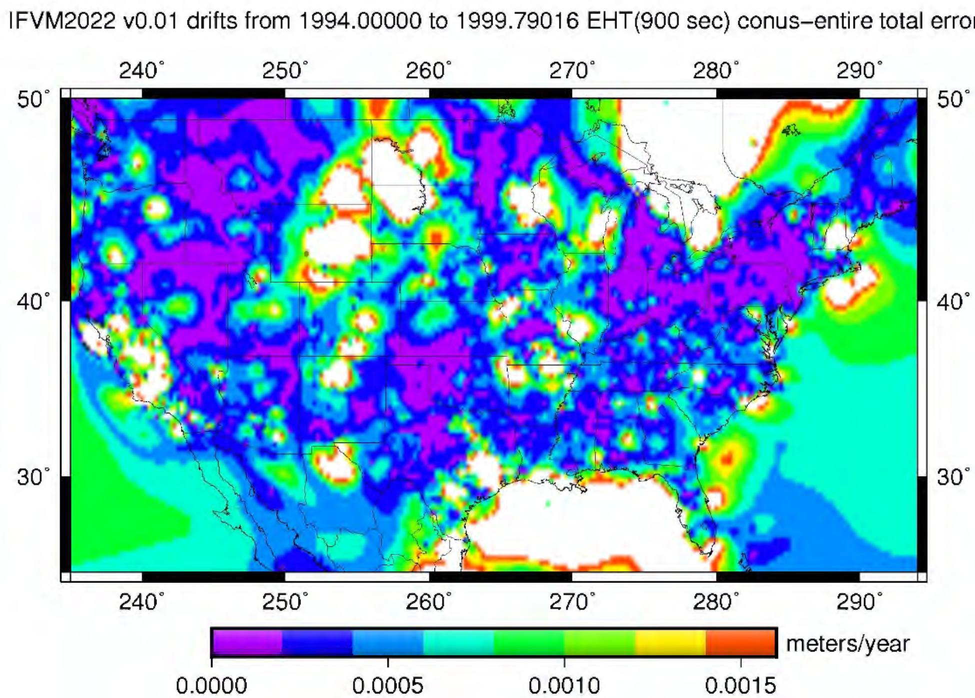


Figure 14: Uncertainties in ellipsoid height DRIFT (m/y)

Before proceeding a word about gridding is necessary. It is a long-established fact that most gridding algorithms are more stable when known systematic signals are first removed from the input data, so that gridding is performed on smaller (residual) data. Once that is done, a gridded version of the removed systematic signal can be restored, resulting in a gridded version of the entire signal. The idea of gridding residuals was considered for this experiment, but was discarded for a number of reasons. The most pressing was time. The build software was adapted from NADCON and VERTCON which did not rely upon remove/grid/restore, since no systematic signals were known a-priori in those fields. Modifying the software to do so would have delayed an already-overlong experiment. Additionally, the easiest "known" signal to remove (rotation of the tectonic plate) would not have yielded small residuals west of the Rockies, which would then lead to a choice of adopting additional systematic models to remove. This author was simply not given the time to investigate those adequately. In the end, time was a factor, but in the future, good science should allow for more adequate gridding techniques.

4.2 Example of Shift Grid (CONUS, 1999.79016)

There were a total of 205 CORS at this epoch with either a brief discontinuity or a coordinate function that is continuous through the earthquake (and thus its "jump" is listed as 0.000 meters). Note that based upon the earlier equation for a radius based on the magnitude of an earthquake, one should not expect to see any shifts outside of about a 500 km radius for this Mw 7.1 earthquake. Nonetheless, a full country-wide set of plots is shown for a few reasons: 1) Because "shift grids" would be nationwide, for simplicity of functionality if encoded into an IFVM and 2) just for the sake of curiosity to see if a shift, outside that radius, was seen (which might be due to a purely coincidental equipment change around the same day as the earthquake). Zoomed-in grids are provided to give clarity to the local area around the epicenter.

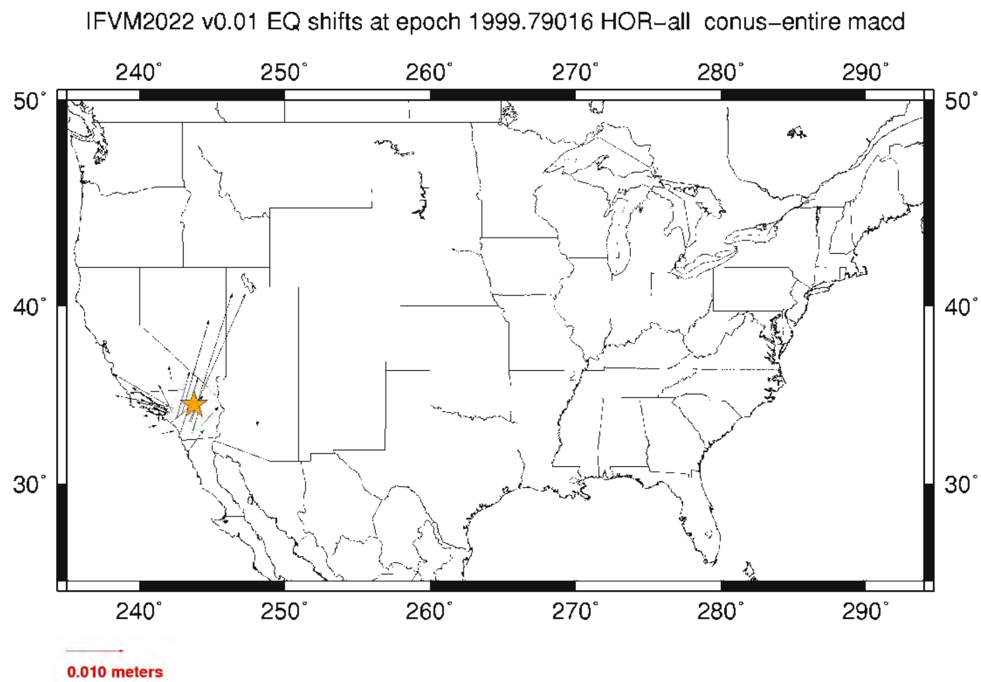


Figure 15: Horizontal SHIFTS at CORSs due to the Hector Mine Earthquake (1999.79016). The epicenter is shown as a star.

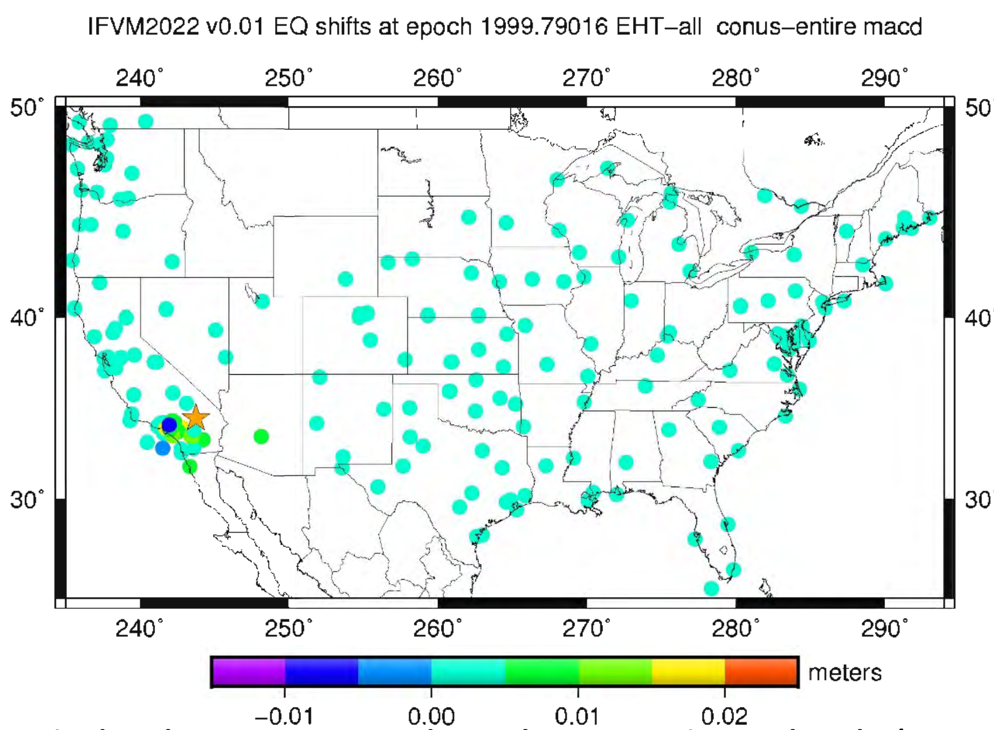


Figure 16: Latitude only SHIFTS at CORSs due to the Hector Mine Earthquake (1999.79016). The epicenter is shown as a star.

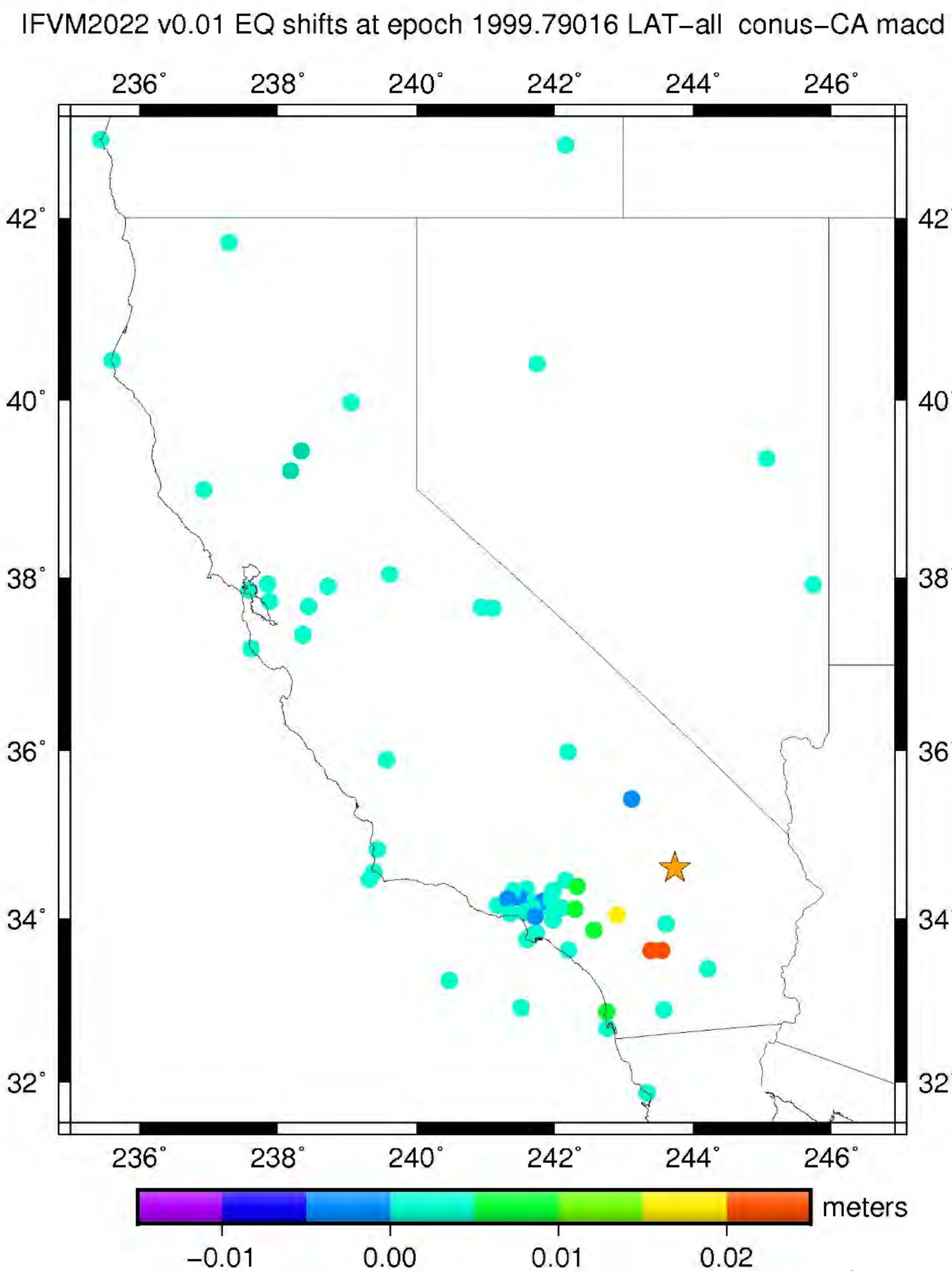


Figure 17: Latitude only SHIFTS at CORSs due to the Hector Mine Earthquake (1999.79016), zoomed in on California. The epicenter is shown as a star.

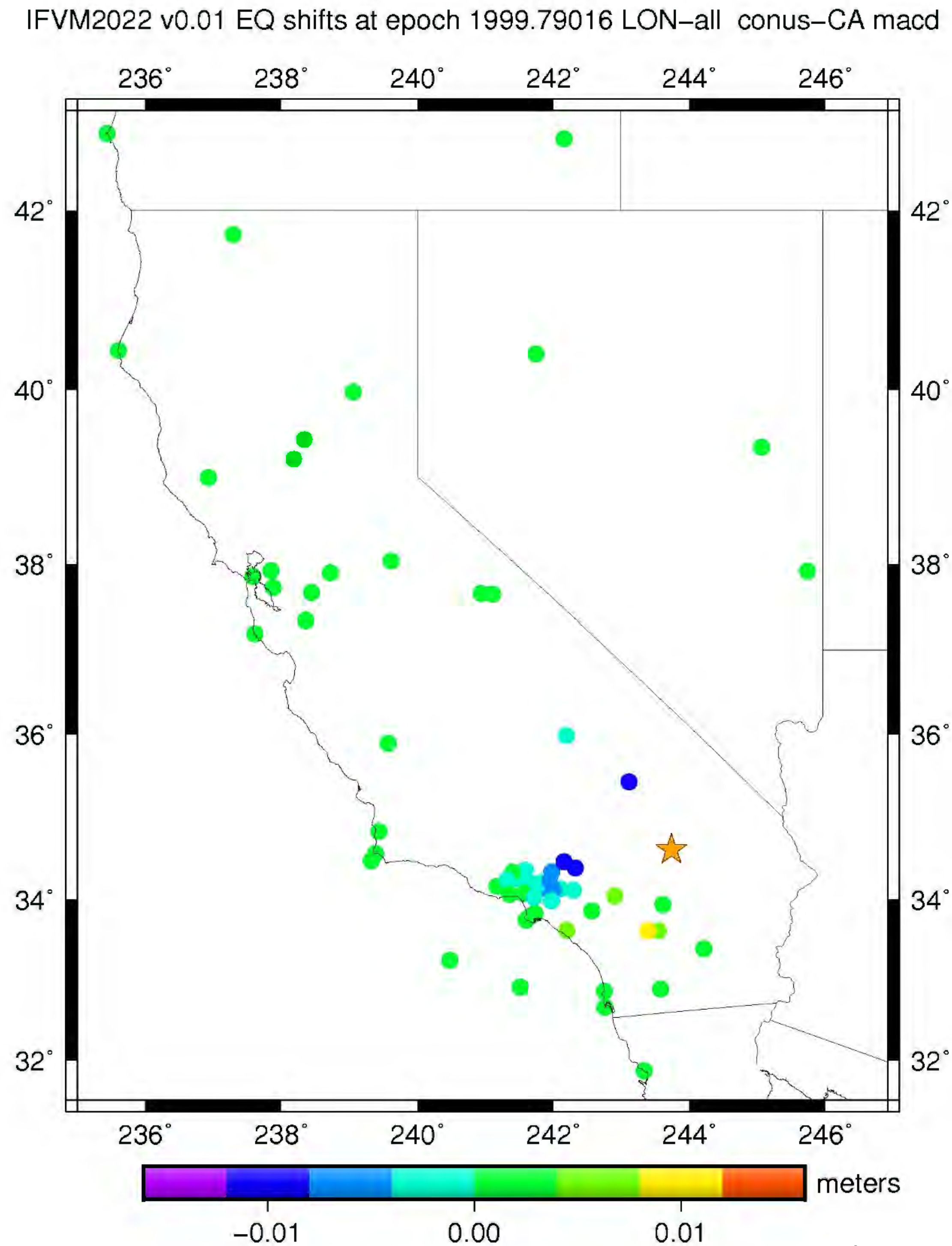


Figure 18: Longitude only SHIFTS at CORSs due to the Hector Mine Earthquake (1999.79016), zoomed in on California. The epicenter is shown as a star.

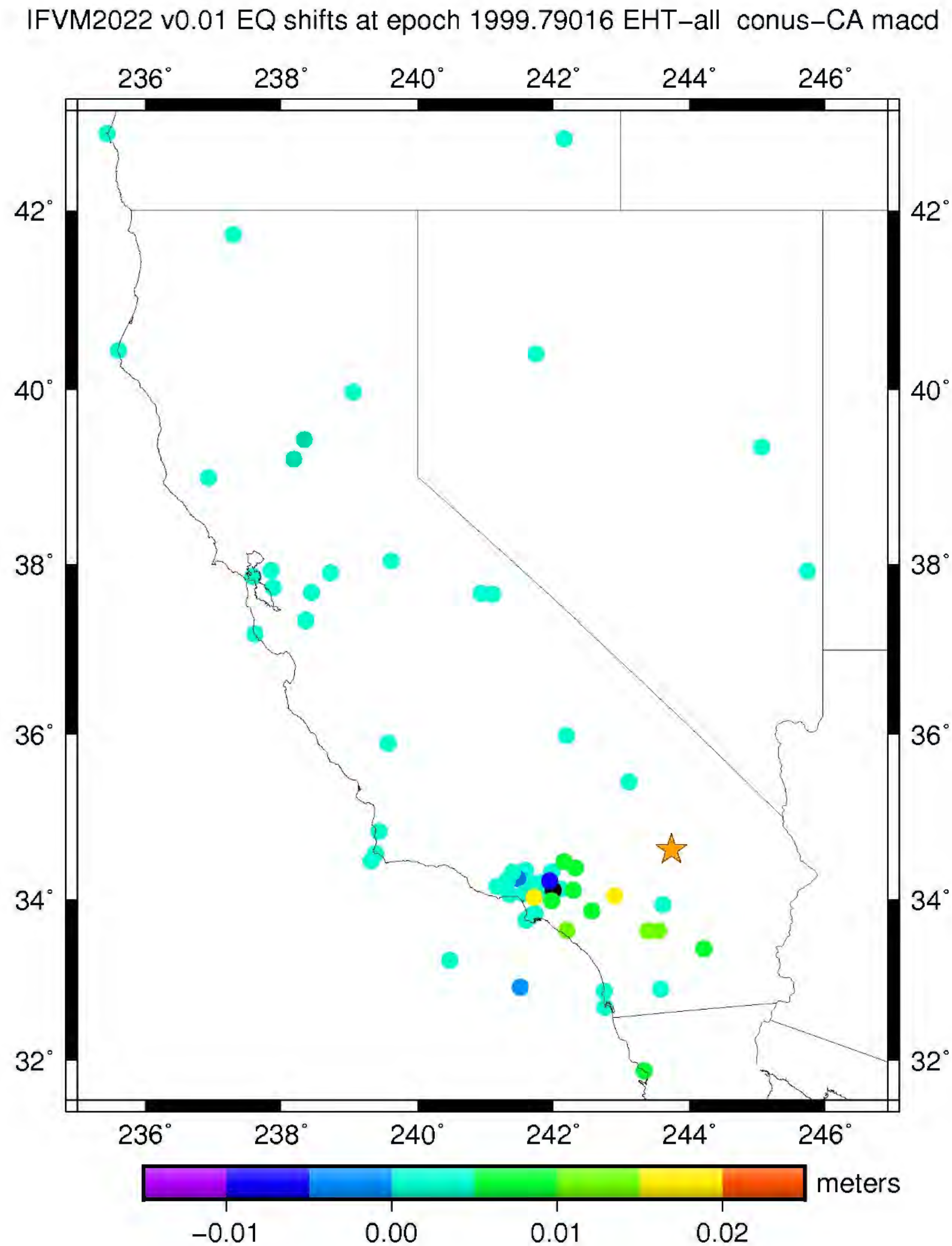


Figure 19: Ellipsoid Height only SHIFTS at CORSs due to the Hector Mine Earthquake (1999.79016), zoomed in on California. The epicenter is shown as a star.

4.2.1 Forcing zero movement across most of the area

The sparseness of the data during shifts, and in particular the earliest shifts (recall we can't "extend" data like velocities were extended in the drift grids) means that there is a tendency for a splines-in-tension approach to have small, but annoyingly non-zero, fluctuations across a region when attempting to create a shift grid. To partially resolve this, a simple filter was applied to the shift grid and the shift error grid. The filter is applied as a simple convolution grid, overlain to the shift or shift error grids, with the following values

$c = 0$	$1000km < d$	(eq)
$c = \frac{\left\{\left[\cos\left(\frac{d - 500km}{500km} \times \pi\right)\right] + 1\right\}}{2}$	$500\ km < d < 1000\ km$	
$c = 1$	$d < 500\ km$	

Where *d* is the distance from any given grid node to the epicenter of the earthquake, and *c* is the value of the convolution grid at that grid cell. For the Hector Mine earthquake (1999.79016), that convolution grid looks like this:

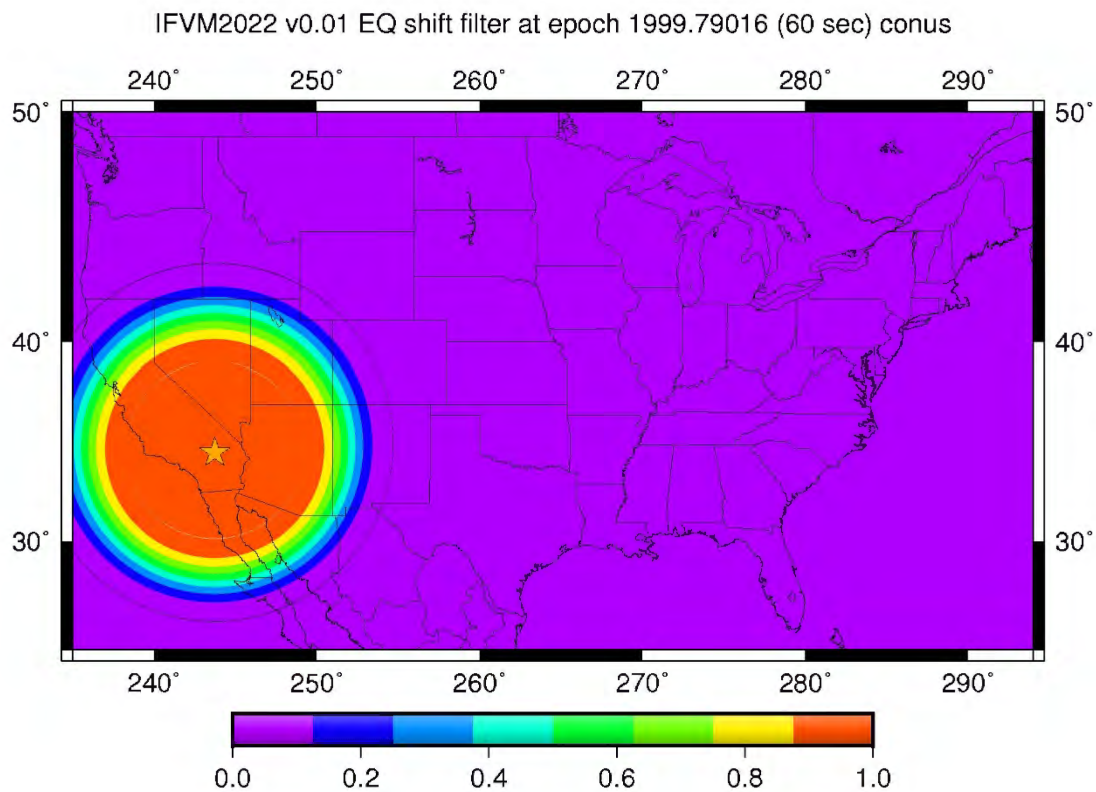


Figure 20: The convolution filter for the Hector Mine Earthquake (1999.79016)

The splines-in-tension-based shift grid was then convolved with the convolution filter grid. What this means is that within 500 km of the epicenter, the surface formed by gridding shift data will be unaltered. Then from 500 km to 1000 km, there will be a slow fall-off of that grid, until it is forced down to a value of 0.000 meters. Outside of 1000 km, the shift grid is forced to be 0.000 meters. A similar impact occurs in the shift error grid.

Undoubtedly arguments can be made for much more elegant solutions than this. The first, most obvious one, is to use equation 1 to customize the enforced "zero movement" radius based upon the magnitude of each quake. However, such refinements will not be performed since (as will be discussed later), this CORS-only approach simply does not contain enough shifts, and certainly no shifts of acceptably large magnitude, to make the "gridding of shifts at CORSs" a viable approach. More on that later.

But if shift grids in an IFVM are to be truly restricted to CORS-only data in any sort of daily autonomous fashion, very little extraneous information (type of earthquake, maximum expected shift, etc.) is available. As such, the intent of this filter is only to enforce a reasonable "zero motion" condition when an earthquake is "far away", while allowing the "nearby" CORS data to fully shape the local shift grid.

The original, and convolved, versions of ellipsoid height shifts due to the Hector Mine earthquake can be seen below.

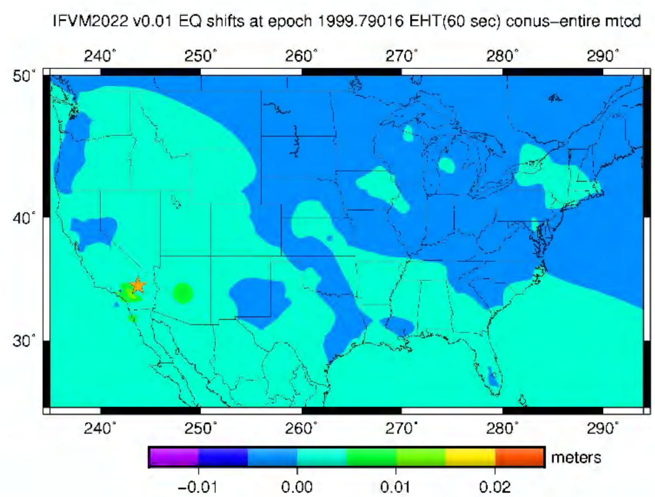


Figure 21: The original, unconvolved/unfiltered shift grid based on splines in tension

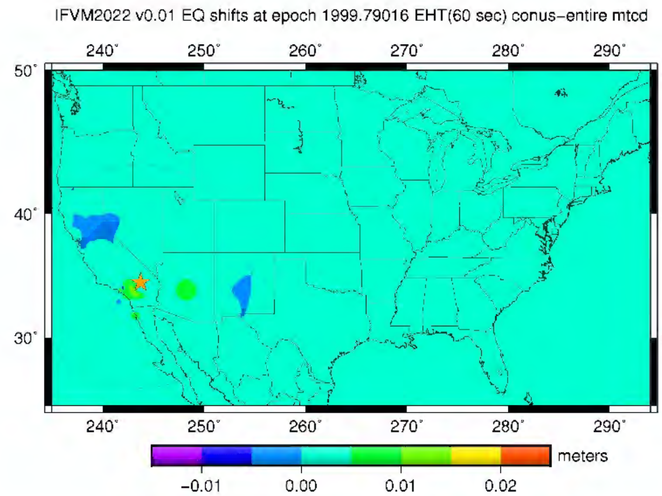


Figure 22: The convolved/filtered ellipsoid height shift grid based on splines in tension, forcing a tapered-to-zero value outside of 1000 km from the epicenter

Although there aren't *large* extraneous signals far from the earthquake at distances beyond 1000 km, they nonetheless do exist at the +/- 5 millimeter level, so are reduced entirely to zero through the convolution filter.

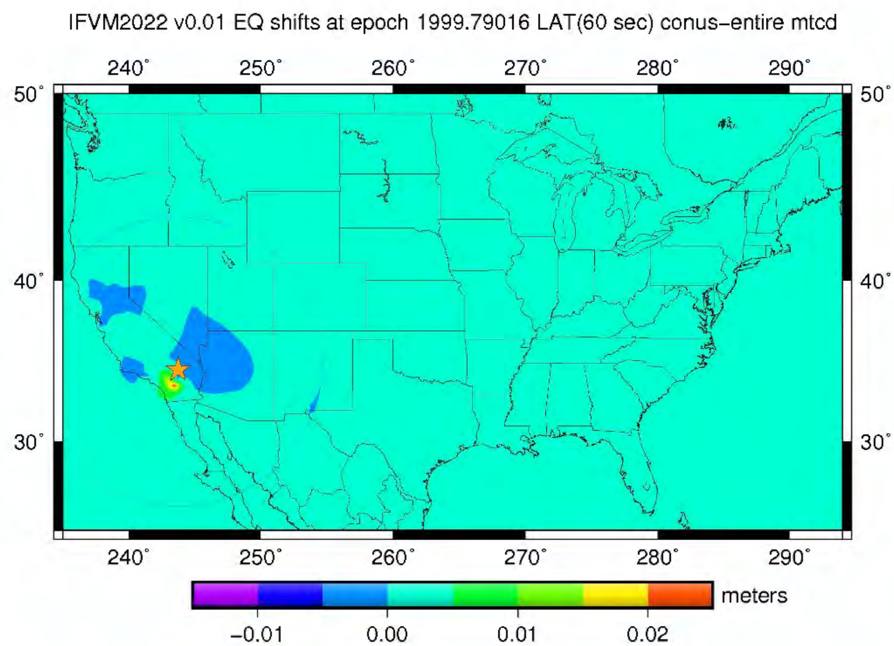


Figure 23: Distance-filtered latitude shifts from the Hector Mine Earthquake

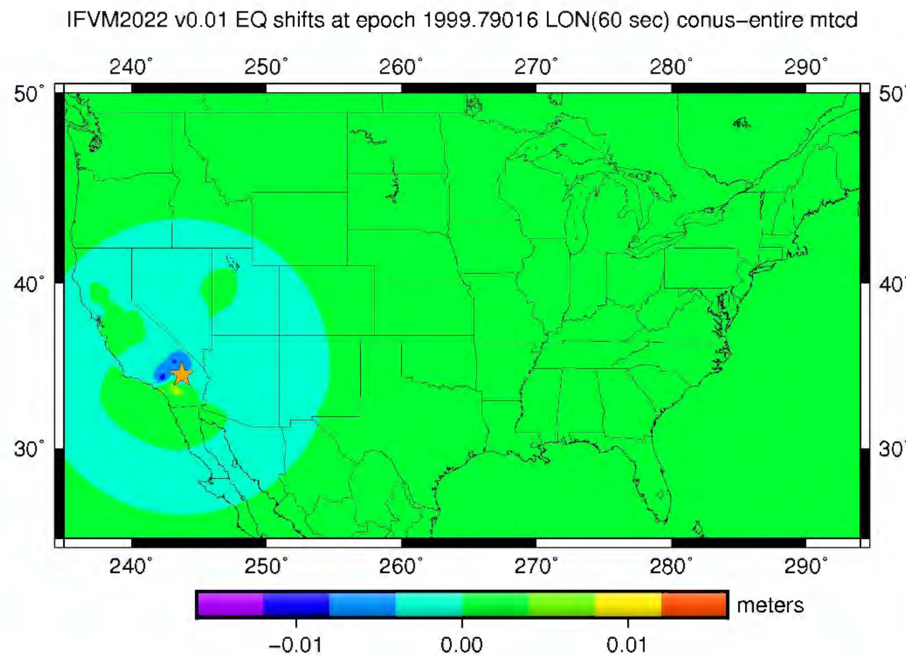


Figure 24: Distance-filtered longitude shifts from the Hector Mine Earthquake

In similar ways, the error grids were also distance filtered. They are not shown, so as to add some semblance of brevity to this section.

5 Accessing the grids

Creating the grids for IFVM2022 v0.01 build 20191107 is only part of the story. Those grids must then be accessed to provide the answer to these two questions:

1) On the crust of the Earth, at some given latitude and longitude, from date 1 to date 2, what was the change in latitude, longitude and ellipsoid height?
2) How well do we know the answer to question 1?

In the future, these two questions will be answered through NGS's primary tools NCAT and VDatum. For now, an experimental piece of code was developed for this study in the form of a simple FORTRAN subroutine, called **useifvm.f**. The functionality of that subroutine can be summarized below:

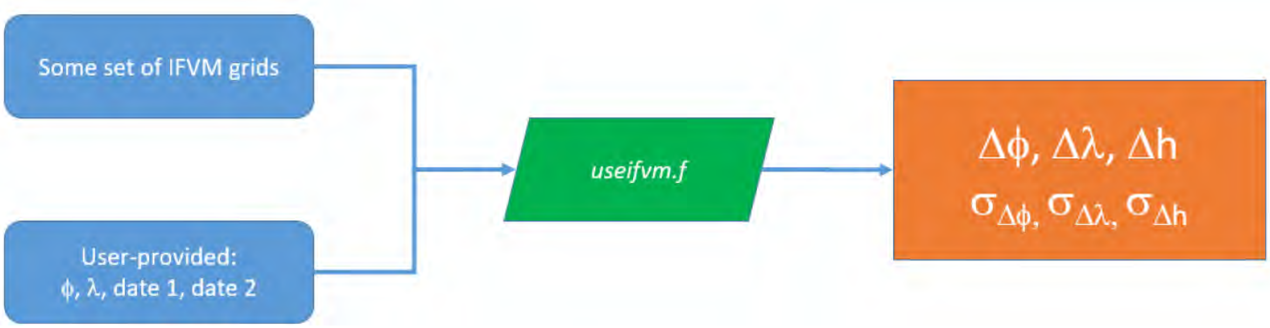


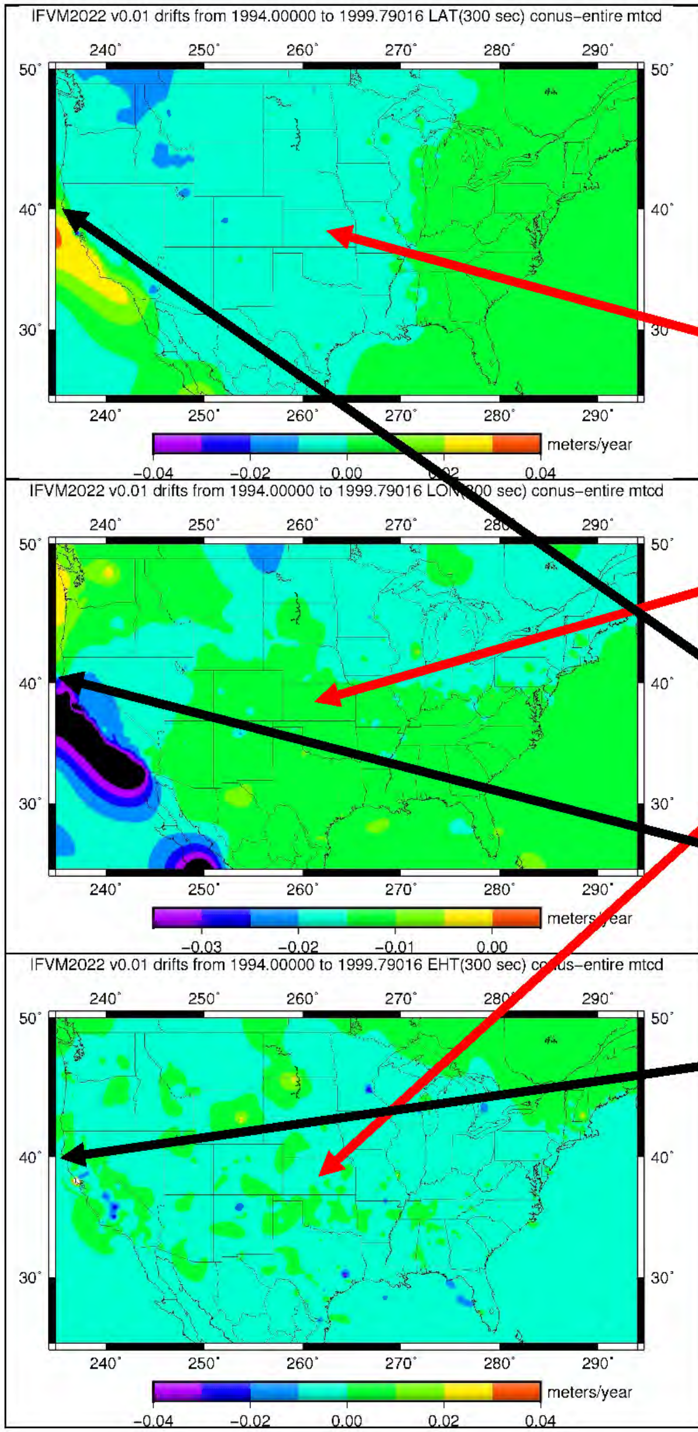
Figure 25: The simple workings of the IFVM

Note that no correlations exist, either between grids or between latitude, longitude and ellipsoid height, so that covariances are not computed.

Two example points were investigated, in order to exemplify how useifvm.f operates, as well as to aide in interpreting the results. The first point we will call "Meades Ranch", as it is in Kansas and more or less in the vicinity of the famed origin point of NAD 27 (ϕ = 39.2° , λ = 261.5°). The second point will be called "Cape Mendicino", as it represents a geodetic mark near Cape Mendicino, which is more or less "ground zero" for three of the five earthquakes which make up the CONUS portion of this IFVM. The following chart reflects first the actual numbers derived from the IFVM.

Shown down the left side are the values of either drifts (in meters/year) or shifts (in meters). On the right hand side are the error grids associated with each shift or drift grid. Although the actual IFVM will operate in arcseconds for latitude and longitude, the table below reflects meters (or meters/year) to aide readers in quickly grasping the magnitudes of the values.

Each shift or drift grid triplicate (and their errors) takes up one page (with 6 total images), with the Meades Ranch or Cape Mendicino values down the middle. On the first page, arrows assist the reader in understanding exactly where the values came from, but as they make the page quite messy, they are left off of later pages.



DRIFT

1994.00000
To
1999.79016

Meades Ranch

$\Delta\phi/\Delta t$ = -3.155 ± 0.272 (mm/y)

$\Delta\lambda/\Delta t$ = -14.283 ± 0.042 (mm/y)

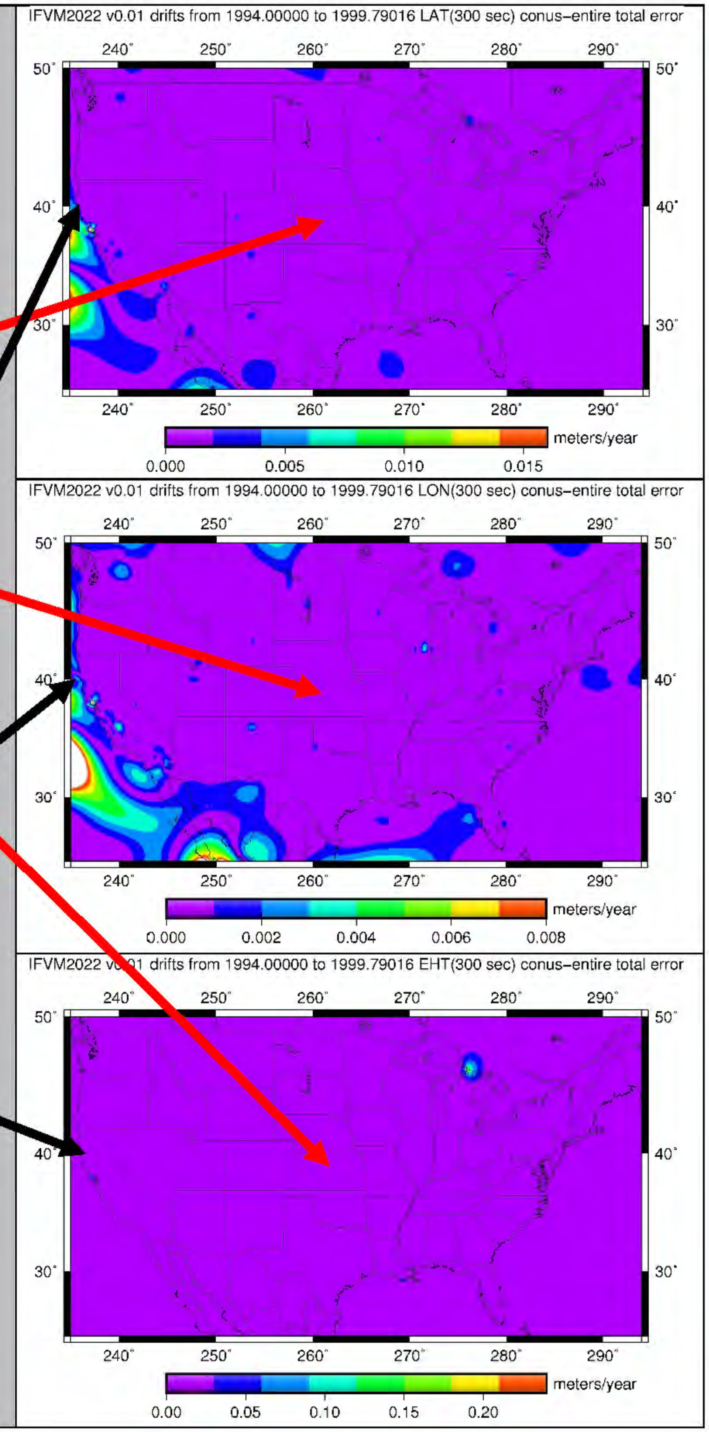
$\Delta h/\Delta t$ = -1.455 ± 0.557 (mm/y)

Cape Mendicino

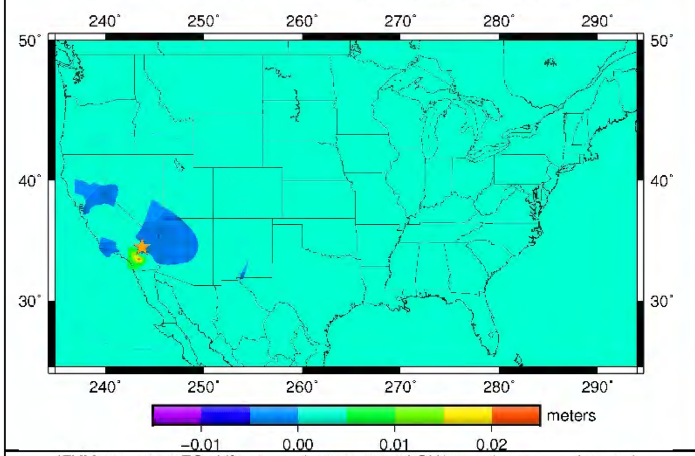
$\Delta\phi/\Delta t$ = +18.472 ± 0.961 (mm/y)

$\Delta\lambda/\Delta t$ = -19.056 ± 0.233 (mm/y)

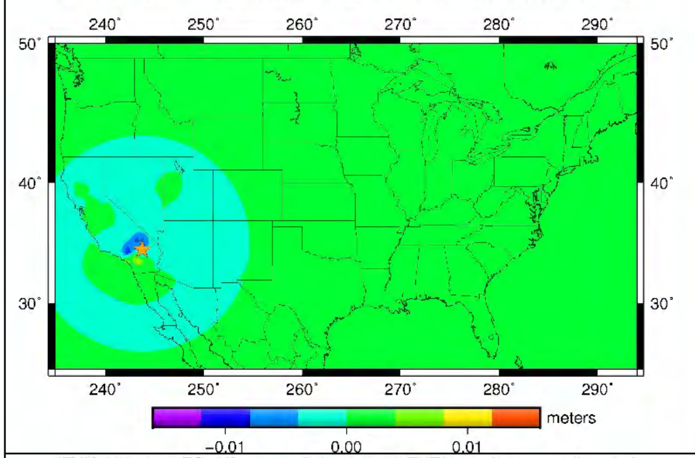
$\Delta h/\Delta t$ = -2.258 ± 0.767 (mm/y)



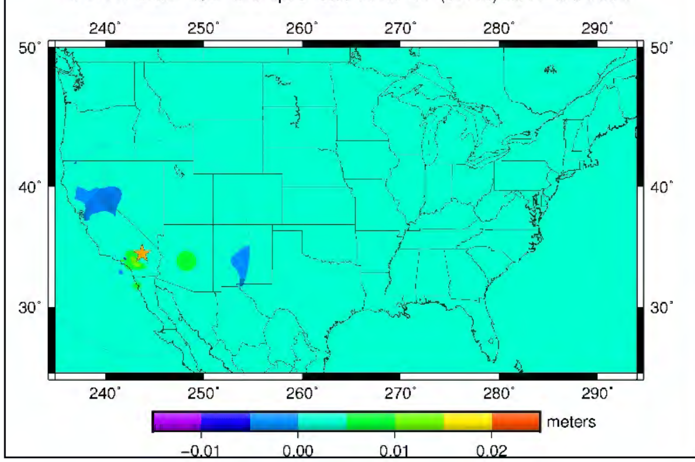
IFVM2022 v0.01 EQ shifts at epoch 1999.79016 LAT(60 sec) conus–entire mtcd



IFVM2022 v0.01 EQ shifts at epoch 1999.79016 LON(60 sec) conus–entire mtcd



IFVM2022 v0.01 EQ shifts at epoch 1999.79016 EHT(60 sec) conus–entire mtcd



SHIFT

1999.79016

Meades Ranch

Δϕ = 0.000 ± 0.000 (mm)

Δλ = 0.000 ± 0.000 (mm)

Δh = 0.000 ± 0.000 (mm)

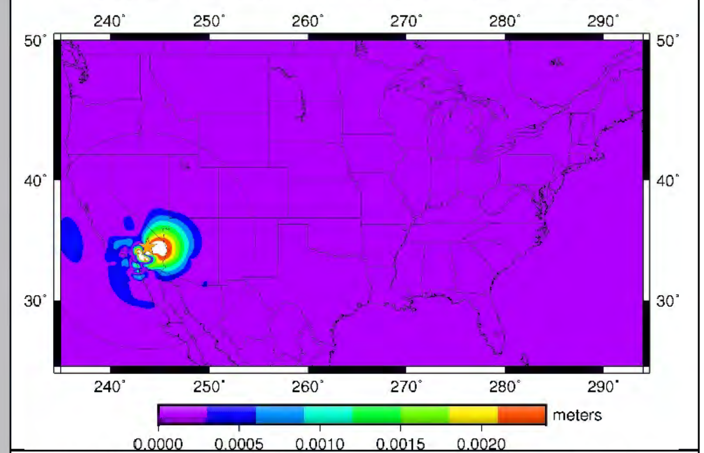
Cape Mendicino

Δϕ = 0.000 ± 0.000 (mm)

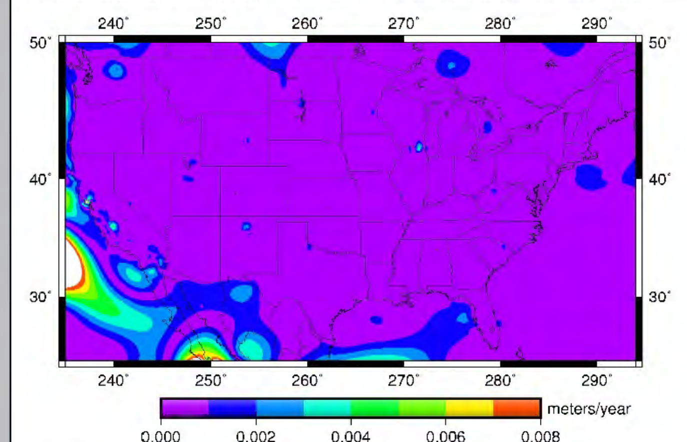
Δλ = 0.000 ± 0.000 (mm)

Δh = 0.000 ± 0.000 (mm)

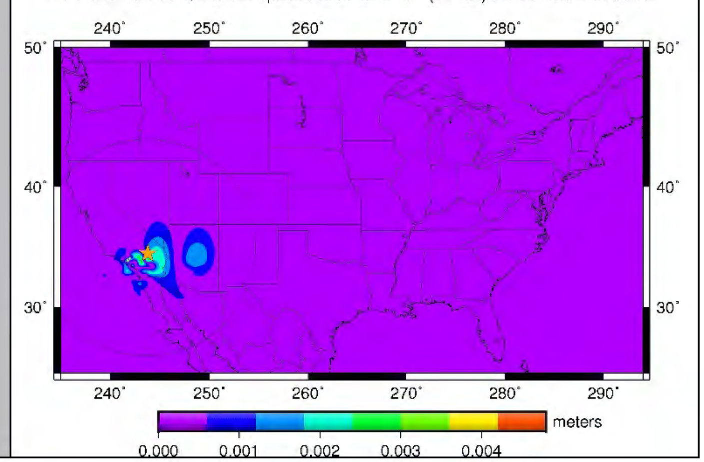
IFVM2022 v0.01 EQ shifts at epoch 1999.79016 LAT(60 sec) conus–entire total error

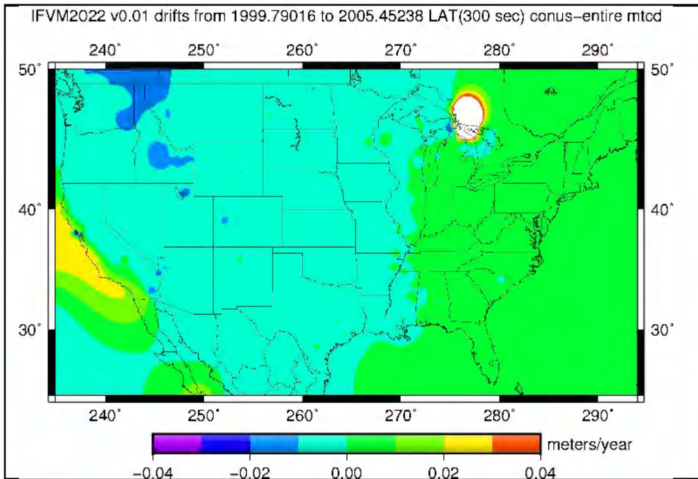


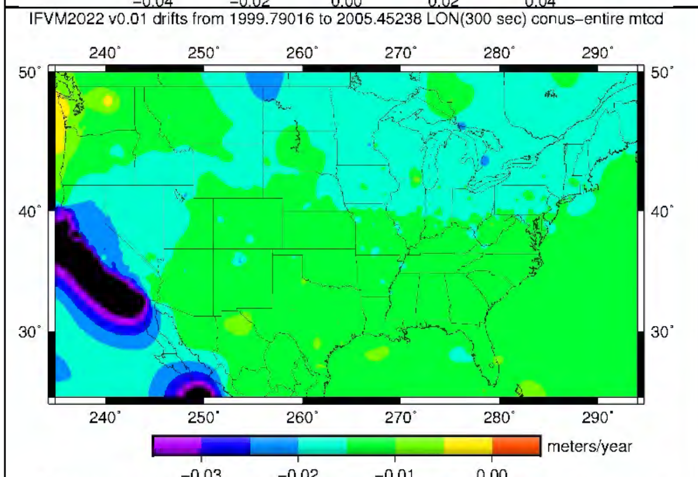
IFVM2022 v0.01 drifts from 1994.00000 to 1999.79016 LON(300 sec) conus–entire total error

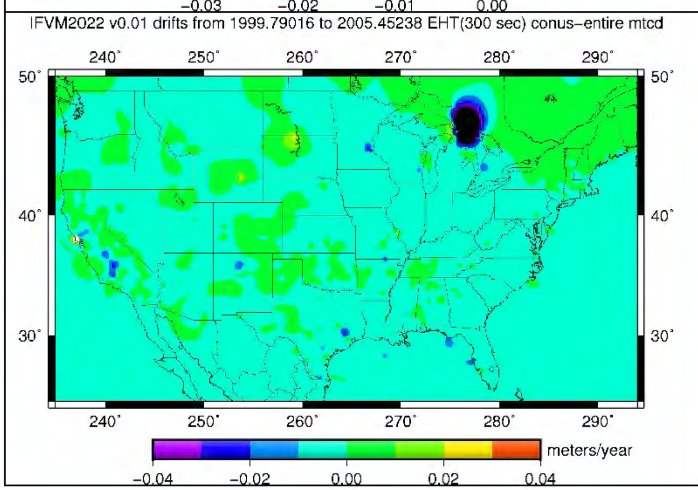


IFVM2022 v0.01 EQ shifts at epoch 1999.79016 EHT(60 sec) conus–entire total error









DRIFT

1999.79016
To
2005.45238

Meades Ranch

$\Delta\phi/\Delta t = -3.409 \pm 0.007$ (mm/y)

$\Delta\lambda/\Delta t = -14.283 \pm 0.042$ (mm/y)

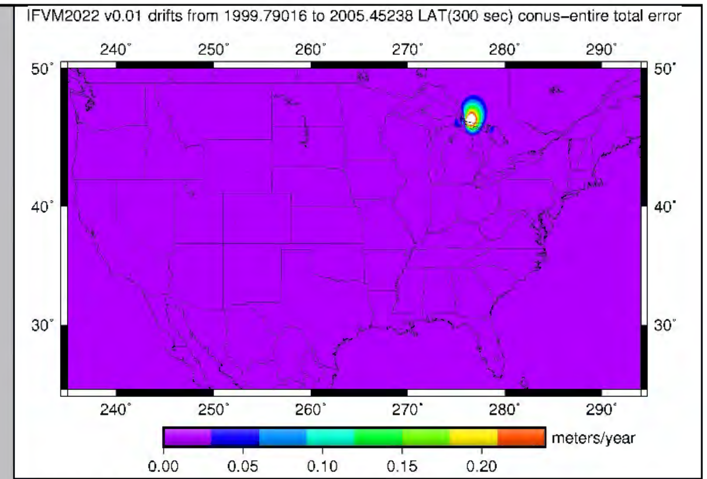
$\Delta h/\Delta t = -1.227 \pm 0.625$ (mm/y)

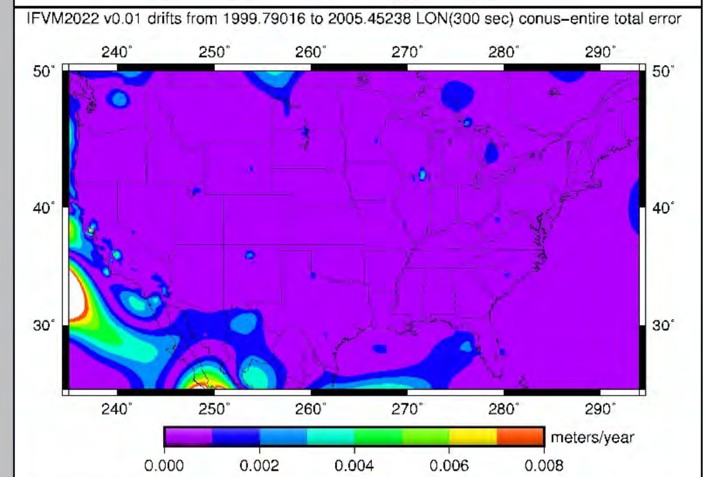
Cape Mendicino

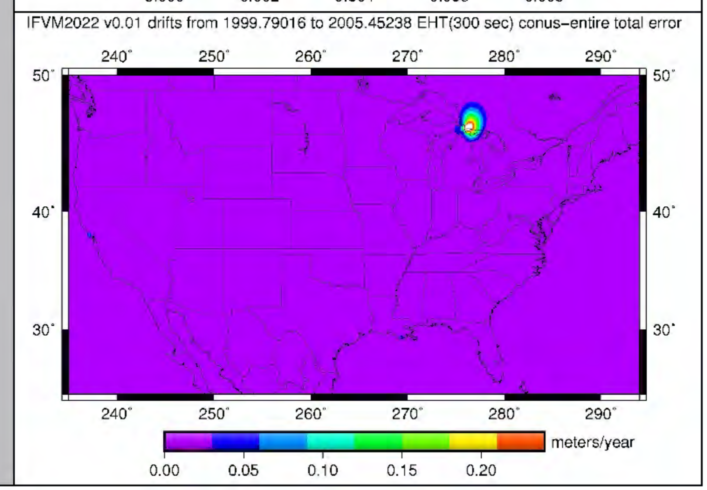
$\Delta\phi/\Delta t = +19.103 \pm 1.181$ (mm/y)

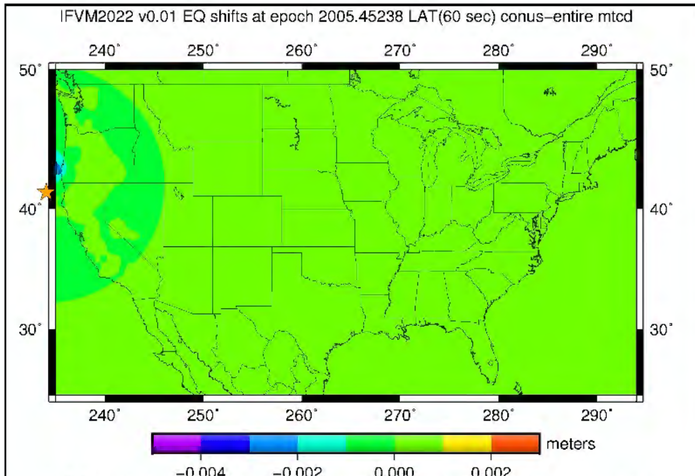
$\Delta\lambda/\Delta t = -19.801 \pm 0.218$ (mm/y)

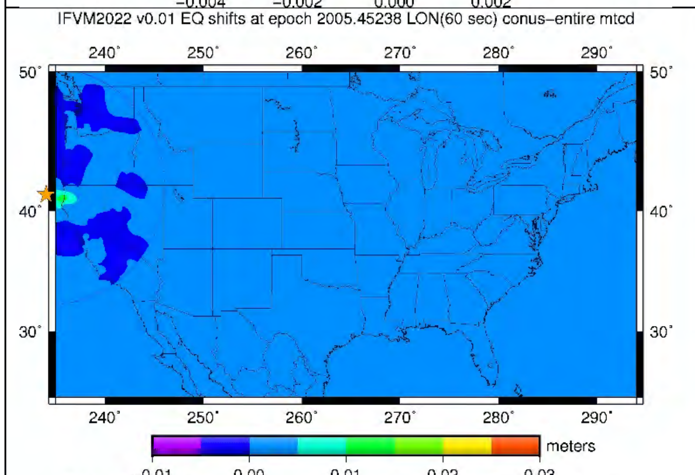
$\Delta h/\Delta t = -1.742 \pm 0.931$ (mm/y)

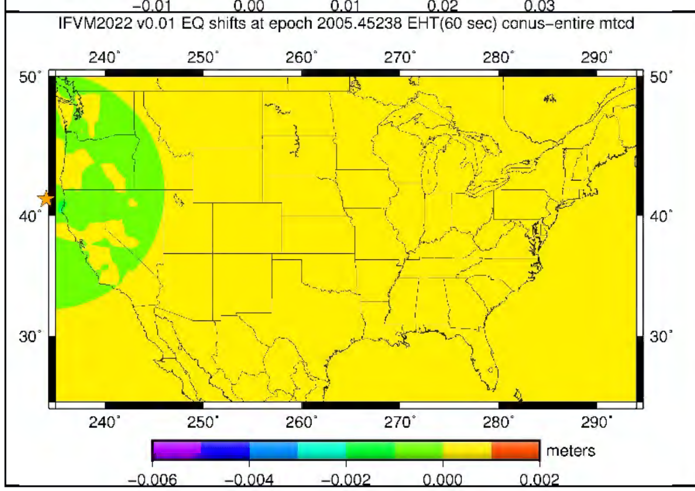












SHIFT

2005.45238

Meades Ranch

$\Delta\phi$ = 0.000 ± 0.000 (mm)

$\Delta\lambda$ = 0.000 ± 0.000 (mm)

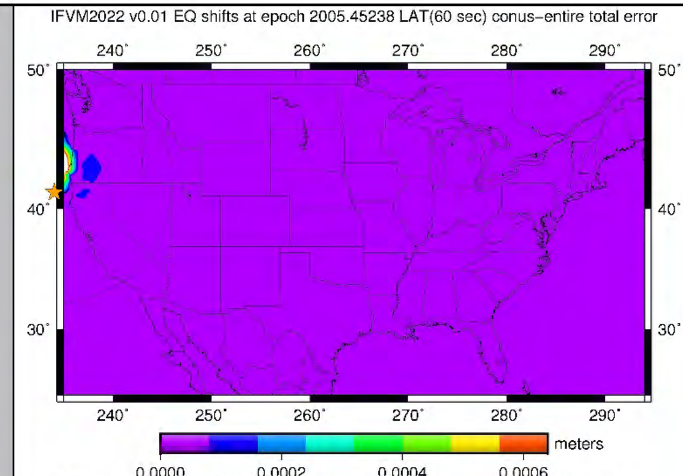
Δh = 0.000 ± 0.000 (mm)

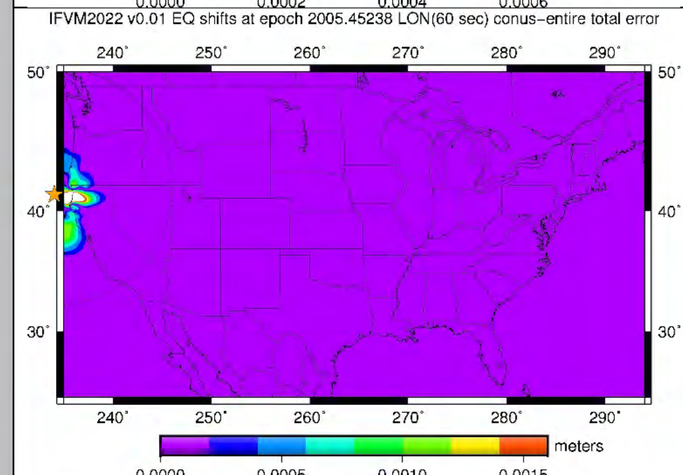
Cape Mendicino

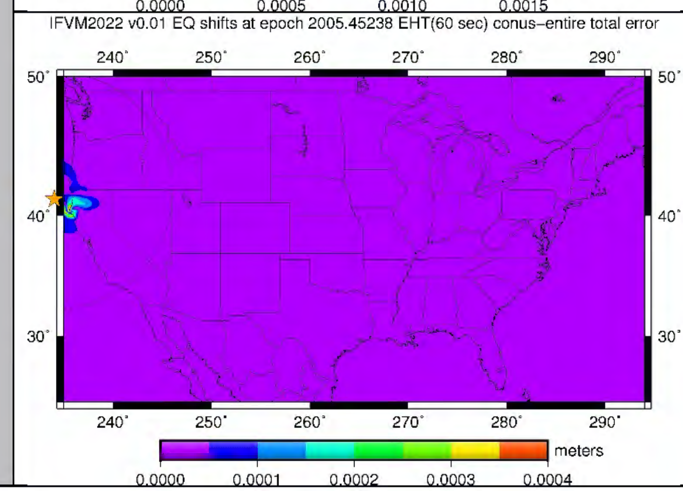
$\Delta\phi$ = -0.636 ± 0.070 (mm)

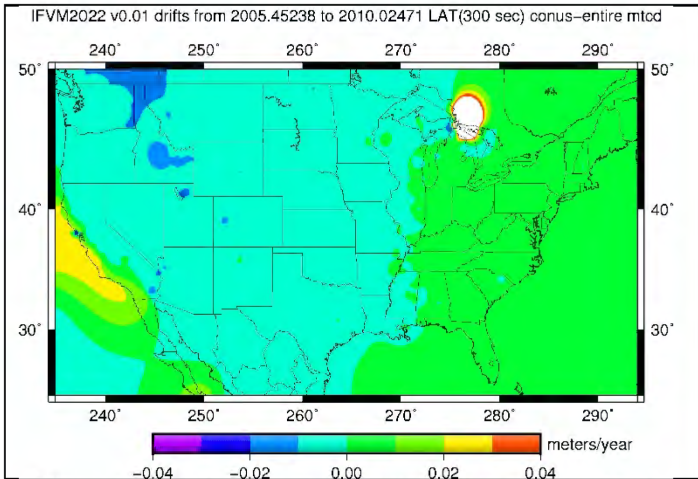
$\Delta\lambda$ = +8.531 ± 0.537 (mm)

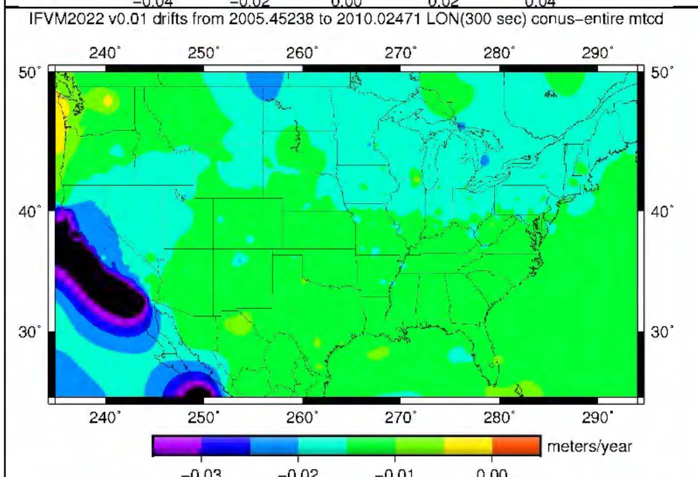
Δh = -3.078 ± 0.299 (mm)

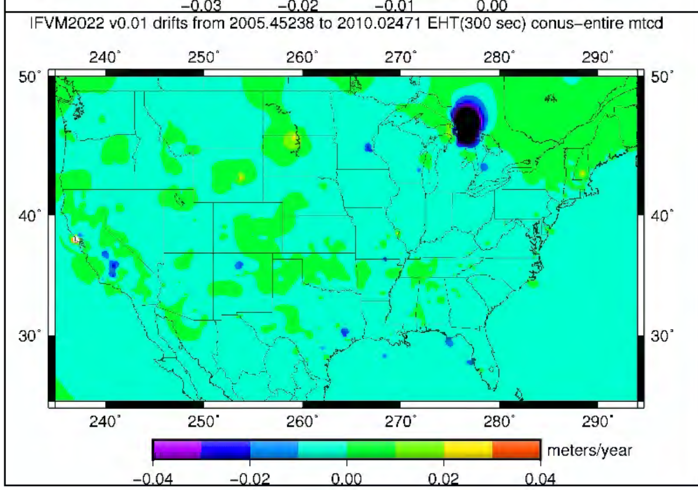












DRIFT

From
2005.45238
To
2010.02471

Meades Ranch

$\Delta\phi/\Delta t = -3.431 \pm 0.005$ (mm/y)

$\Delta\lambda/\Delta t = -14.281 \pm 0.048$ (mm/y)

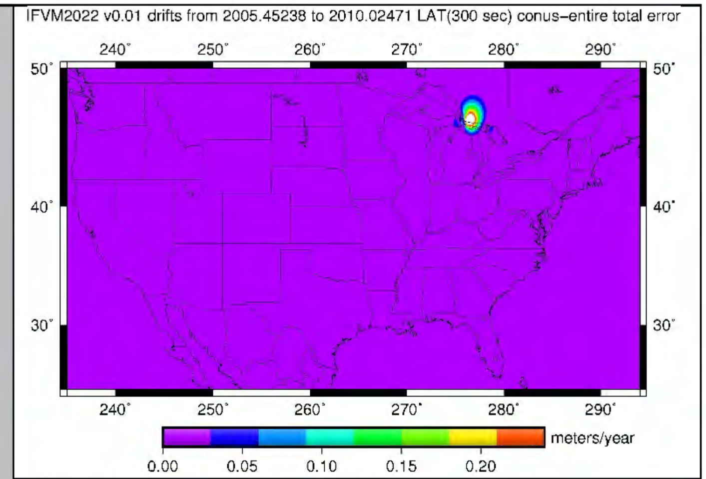
$\Delta h/\Delta t = -1.370 \pm 0.598$ (mm/y)

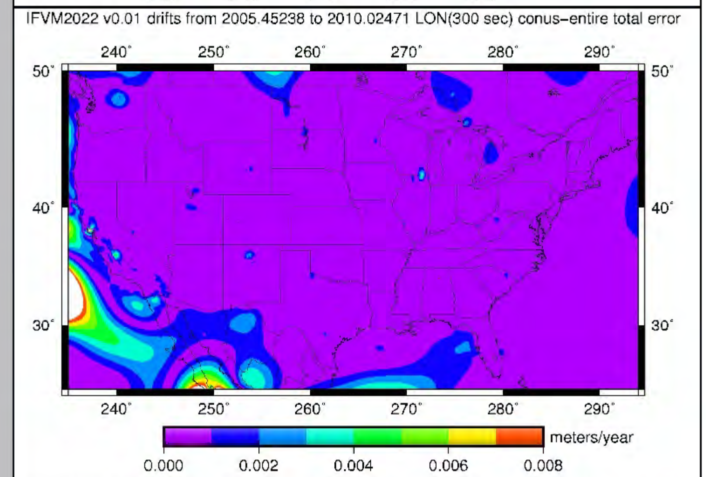
Cape Mendicino

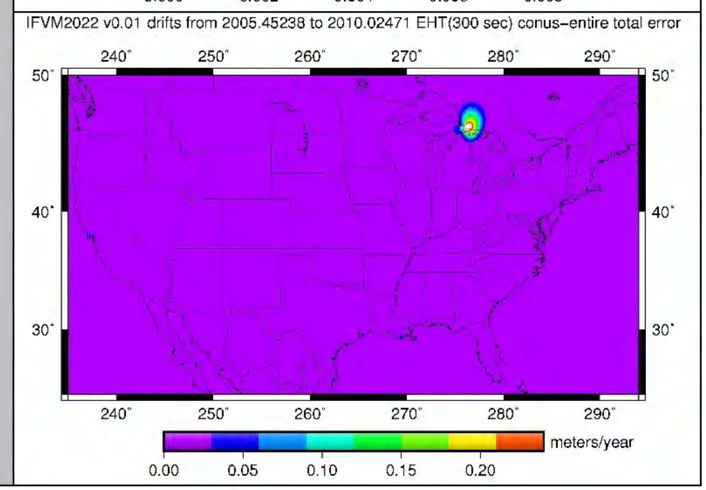
$\Delta\phi/\Delta t = +19.116 \pm 1.217$ (mm/y)

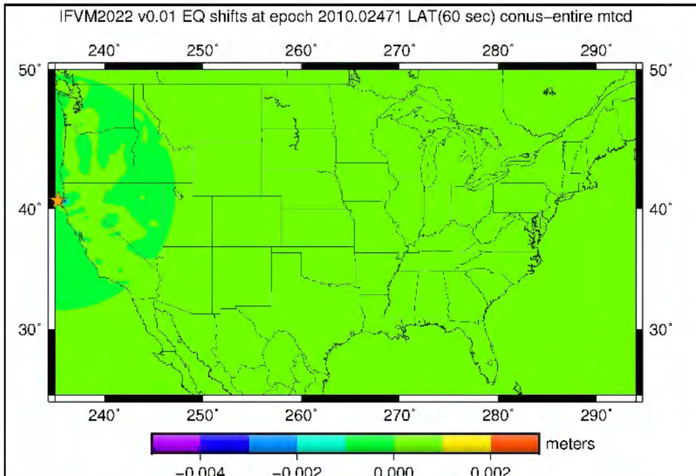
$\Delta\lambda/\Delta t = -19.773 \pm 0.213$ (mm/y)

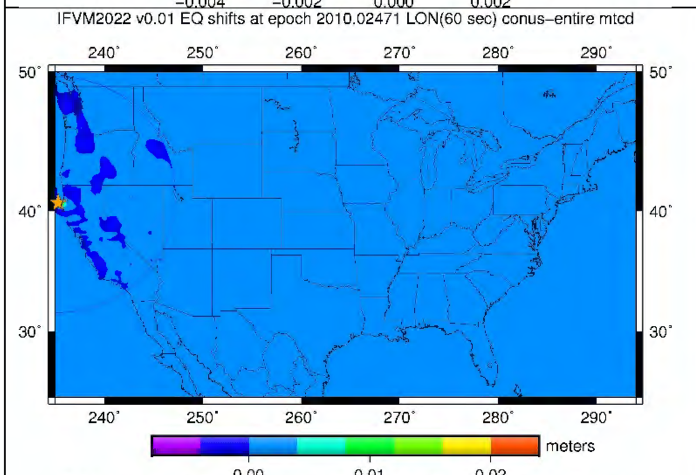
$\Delta h/\Delta t = -1.721 \pm 0.921$ (mm/y)

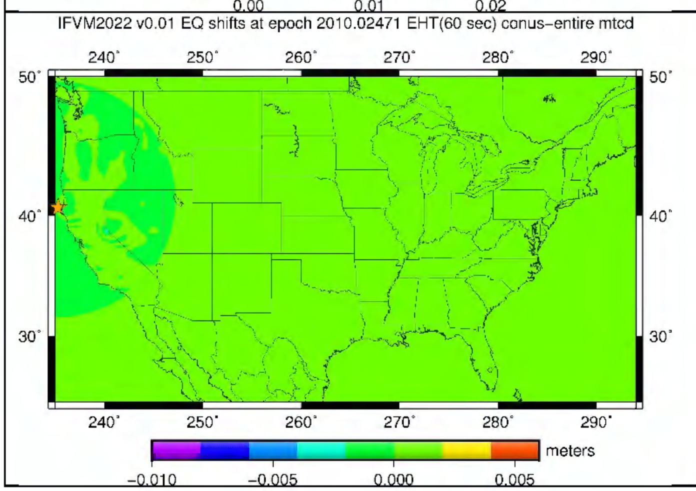












SHIFT

2010.02471

<u>Meades Ranch</u>

$\Delta\phi$ = 0.000 ± 0.000 (mm)

$\Delta\lambda$ = 0.000 ± 0.000 (mm)

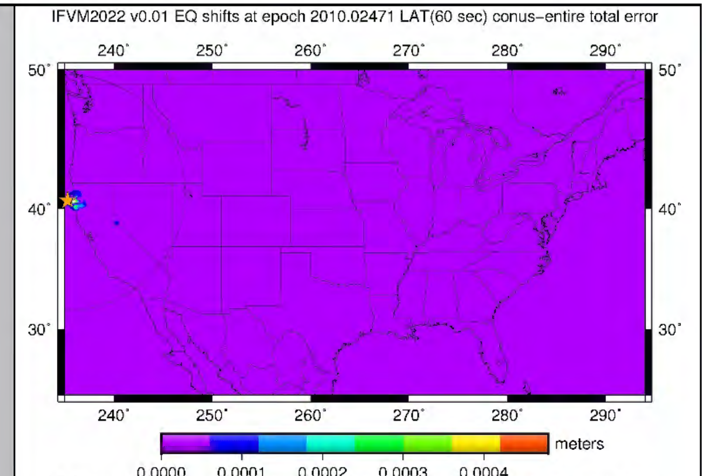
Δh = 0.000 ± 0.000 (mm)

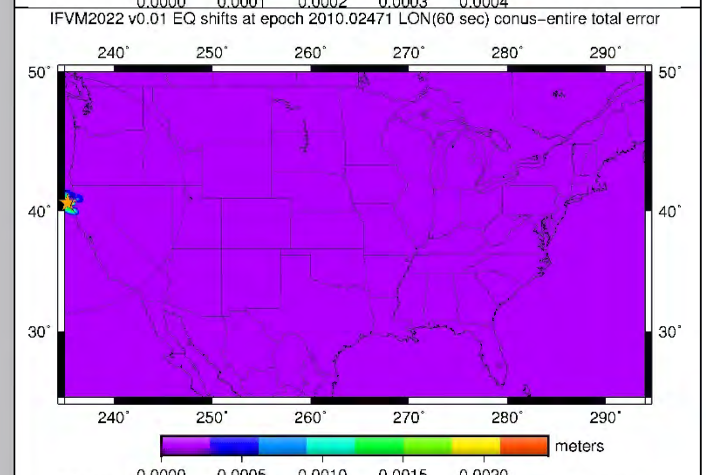
<u>Cape Mendicino</u>

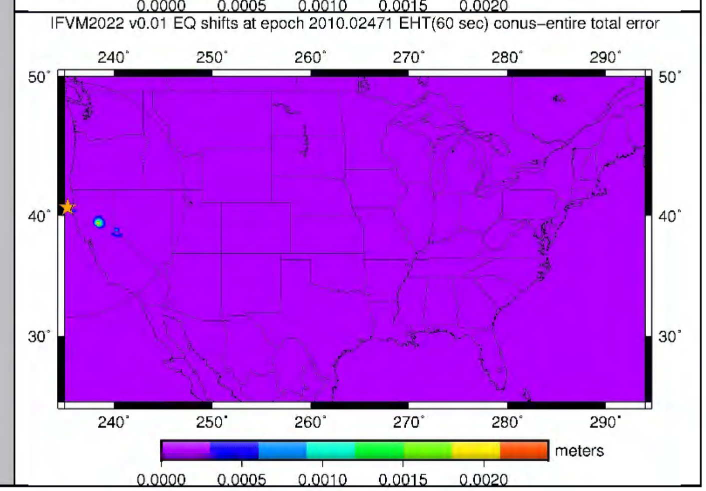
$\Delta\phi$ = -0.005 ± 0.128 (mm)

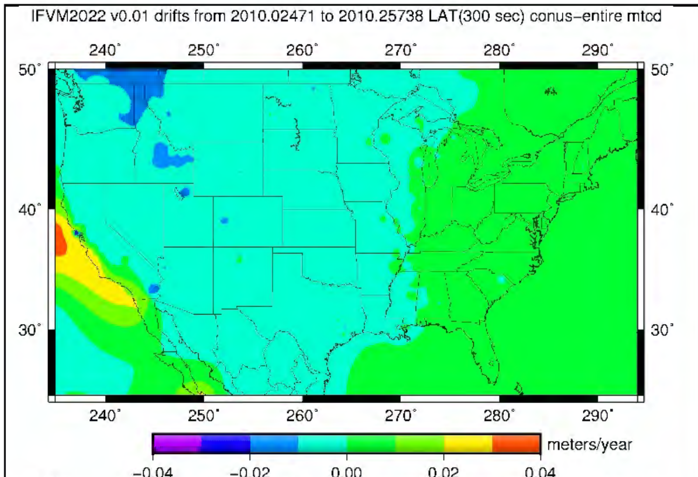
$\Delta\lambda$ = +7.997 ± 0.403 (mm)

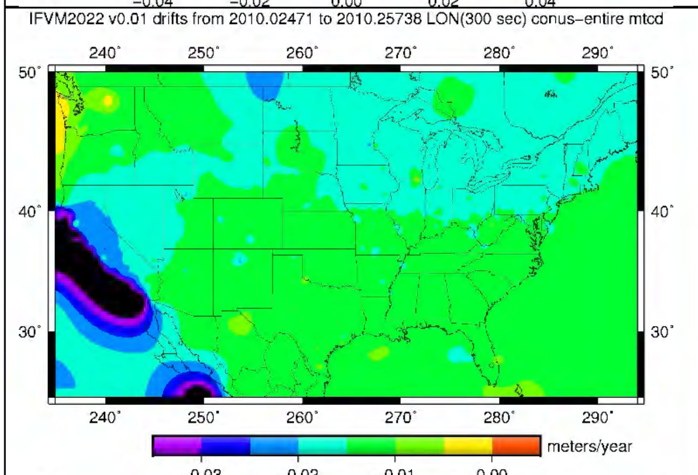
Δh = -0.232 ± 0.389 (mm)

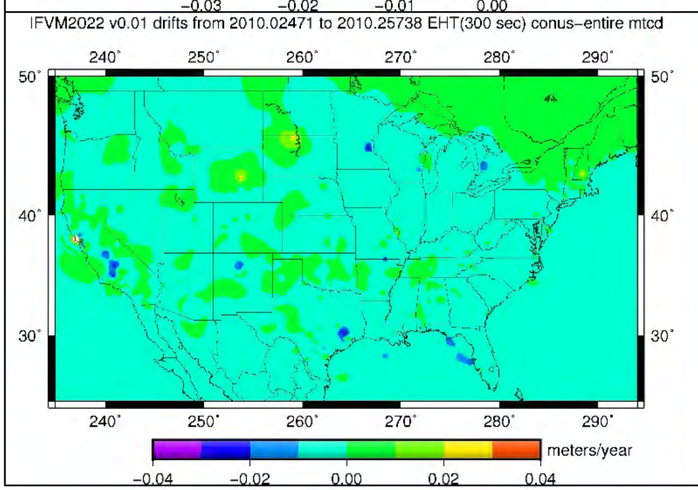












DRIFT

From
2010.02471
To
2010.25738

Meades Ranch

$\Delta\phi/\Delta t$ = -2.859 ± 0.523 (mm/y)

$\Delta\lambda/\Delta t$ = -13.976 ± 0.218 (mm/y)

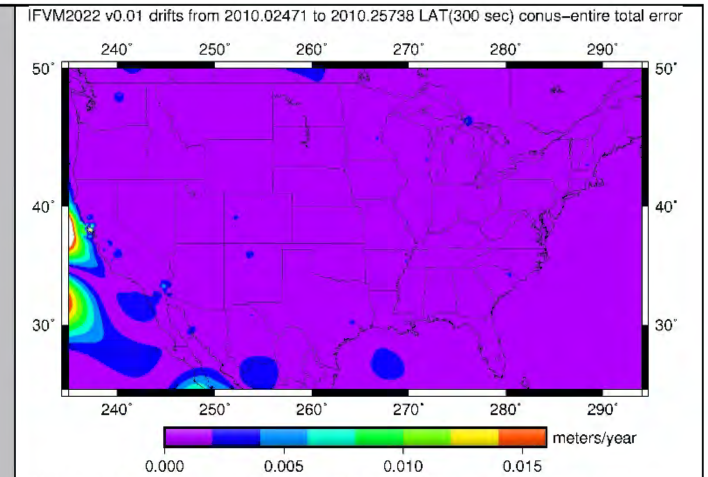
$\Delta h/\Delta t$ = -1.628 ± 0.749 (mm/y)

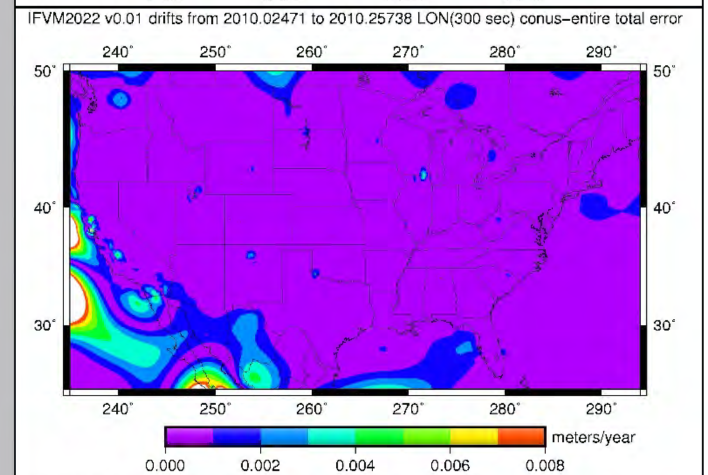
Cape Mendicino

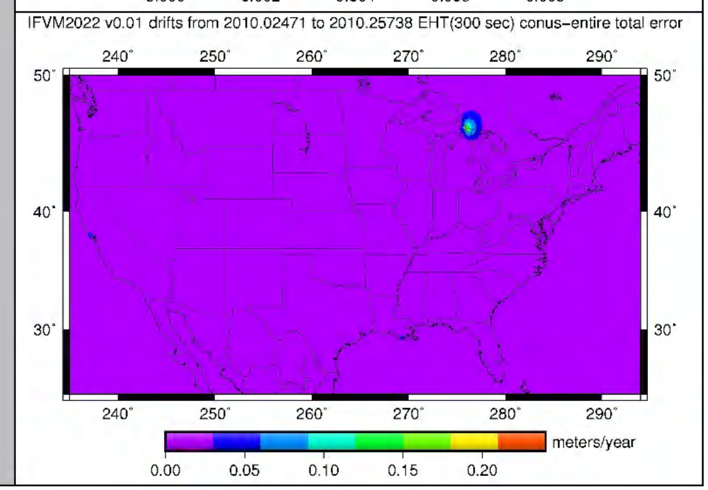
$\Delta\phi/\Delta t$ = +18.835 ± 1.067 (mm/y)

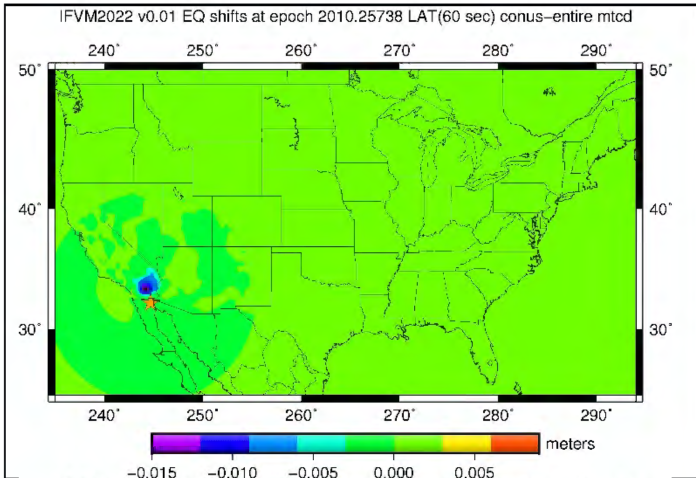
$\Delta\lambda/\Delta t$ = -19.810 ± 0.236 (mm/y)

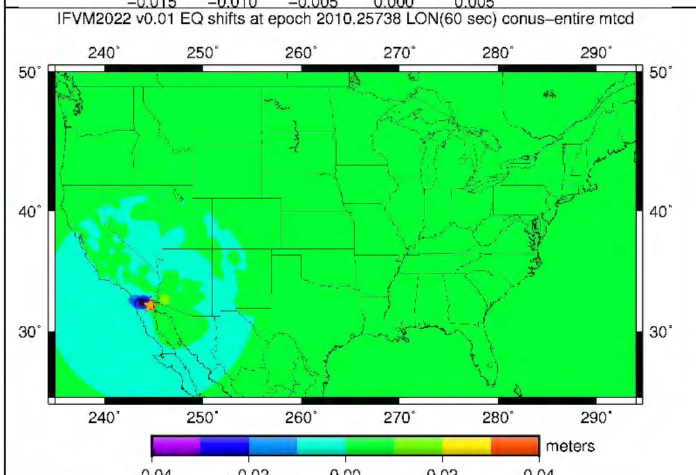
$\Delta h/\Delta t$ = -1.679 ± 0.924 (mm/y)

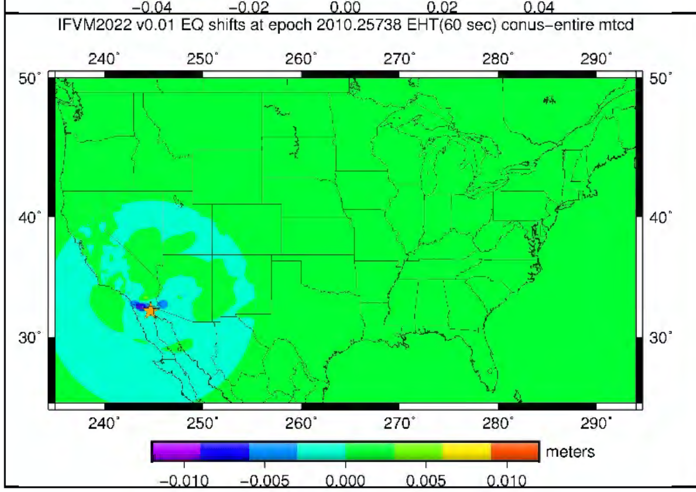












SHIFT

2010.25738

Meades Ranch

$\Delta\phi$ = 0.000 ± 0.000 (mm)

$\Delta\lambda$ = 0.000 ± 0.000 (mm)

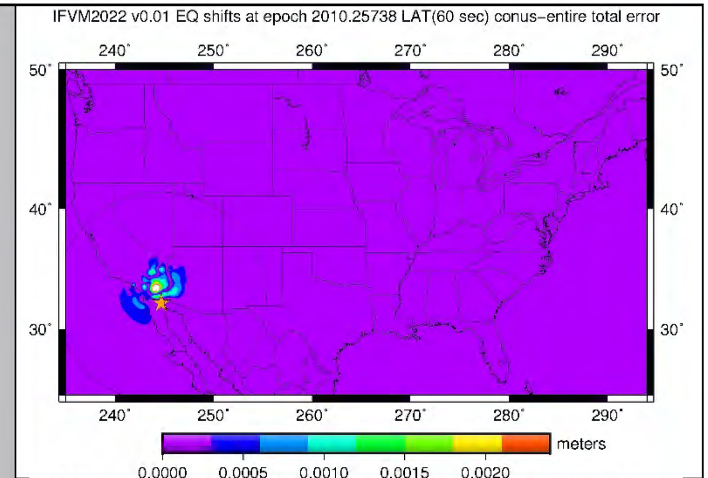
Δh = 0.000 ± 0.000 (mm)

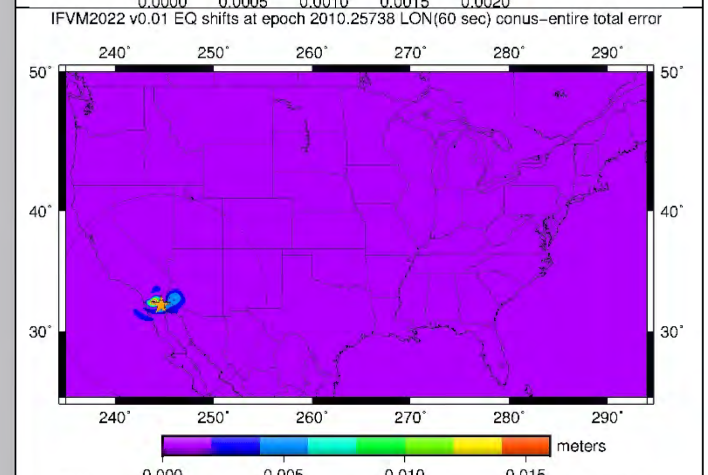
Cape Mendicino

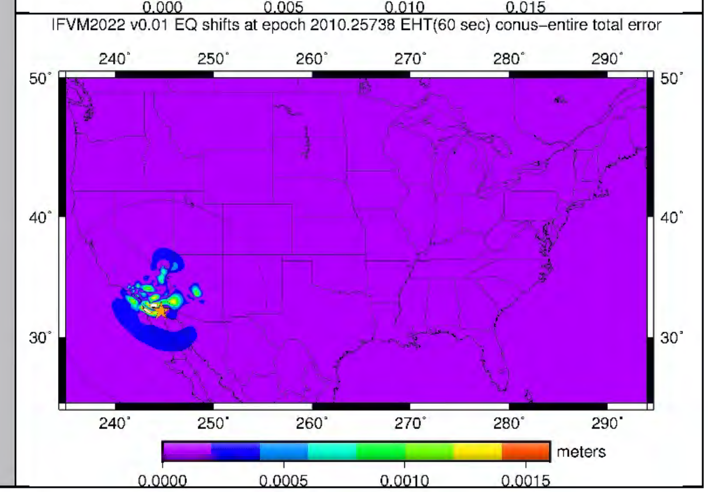
$\Delta\phi$ = 0.000 ± 0.000 (mm)

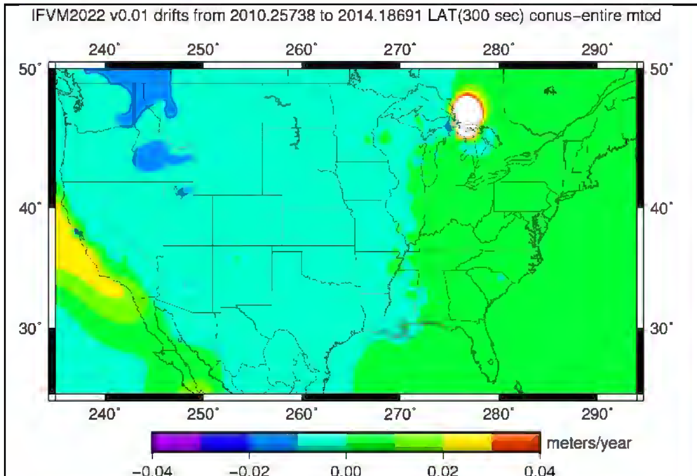
$\Delta\lambda$ = 0.000 ± 0.000 (mm)

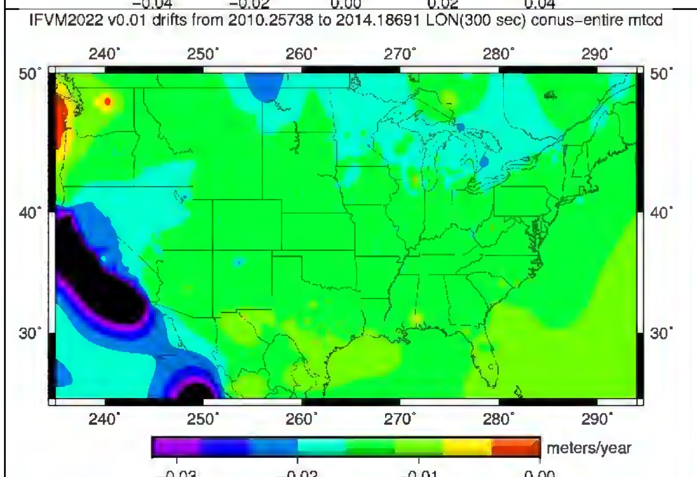
Δh = 0.000 ± 0.000 (mm)

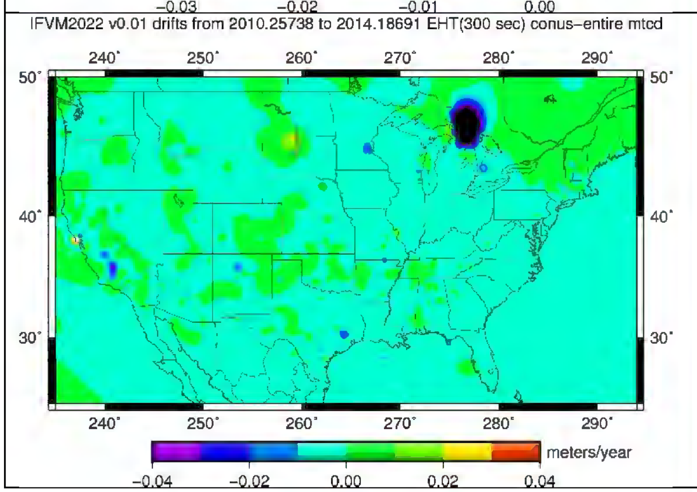












DRIFT

From
2010.25738
To
2014.18961

<u>Meades Ranch</u>

$\Delta\phi/\Delta t = -3.427 \pm 0.048$ (mm/y)

$\Delta\lambda/\Delta t = -14.560 \pm 0.095$ (mm/y)

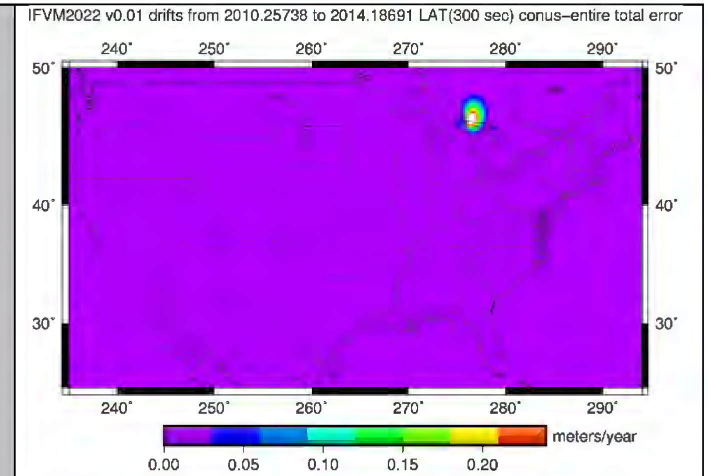
$\Delta h/\Delta t = -1.085 \pm 0.605$ (mm/y)

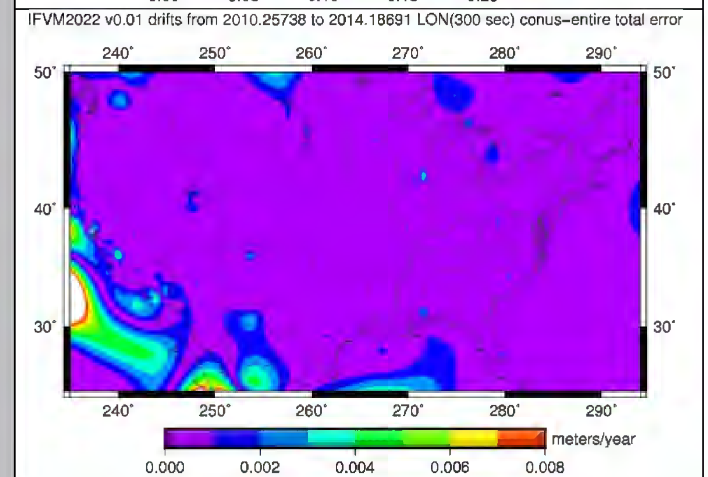
<u>Cape Mendicino</u>

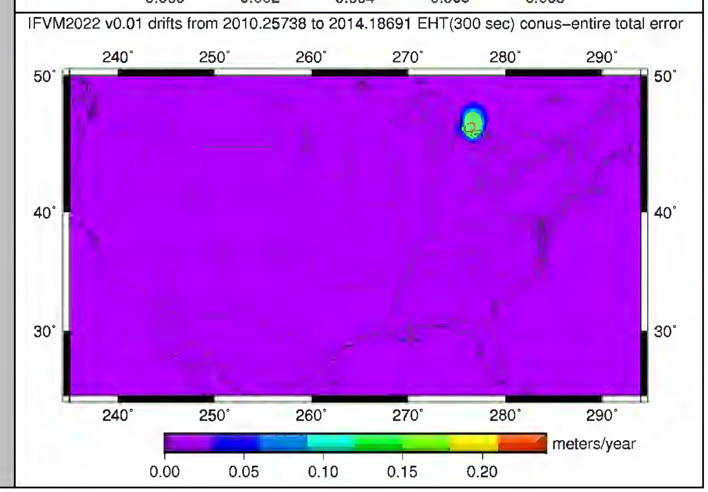
$\Delta\phi/\Delta t = +19.245 \pm 1.355$ (mm/y)

$\Delta\lambda/\Delta t = -20.277 \pm 0.224$ (mm/y)

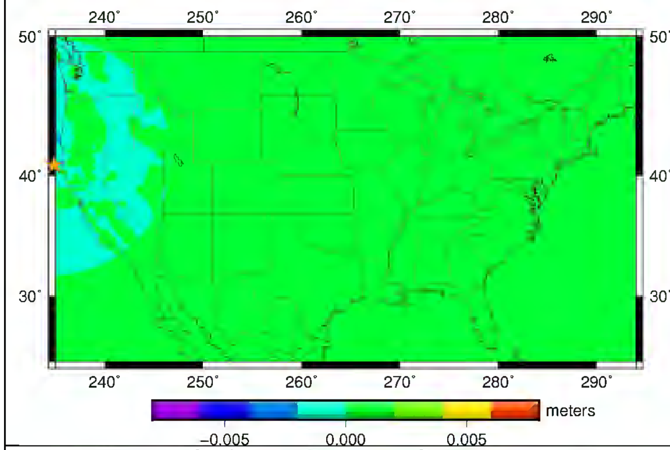
$\Delta h/\Delta t = -1.747 \pm 0.957$ (mm/y)



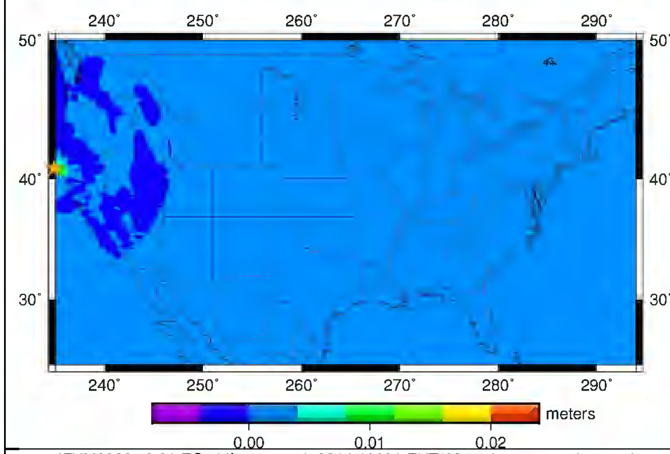




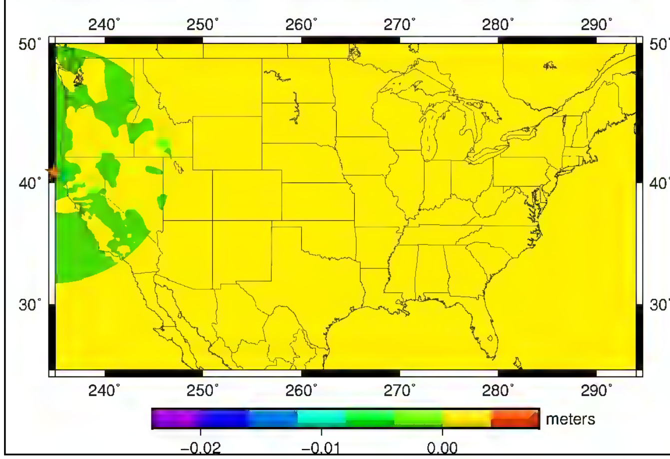
IFVM2022 v0.01 EQ shifts at epoch 2014.18691 LAT(60 sec) conus–entire mtcd



IFVM2022 v0.01 EQ shifts at epoch 2014.18691 LON(60 sec) conus–entire mtcd



IFVM2022 v0.01 EQ shifts at epoch 2014.18691 EHT(60 sec) conus–entire mtcd



SHIFT

2014.18961

Meades Ranch

$\Delta\phi$ = 0.000 ± 0.000 (mm)

$\Delta\lambda$ = 0.000 ± 0.000 (mm)

Δh = 0.000 ± 0.000 (mm)

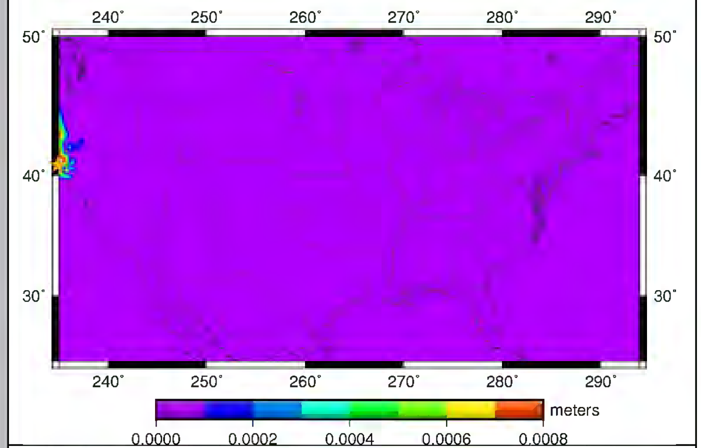
Cape Mendicino

$\Delta\phi$ = +2.525 ± 0.230 (mm)

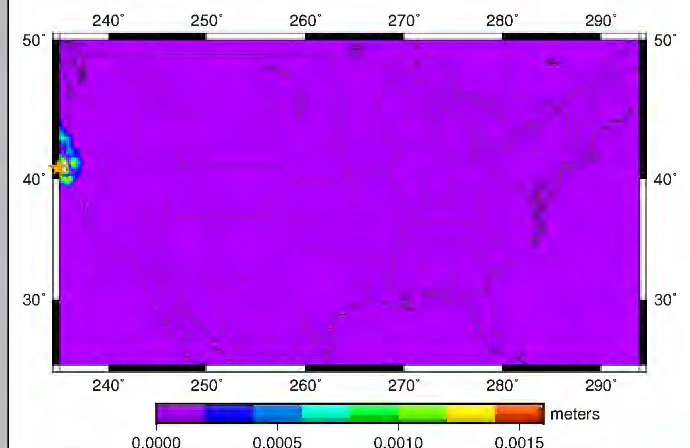
$\Delta\lambda$ = +13.687 ± 0.0.725 (mm)

Δh = -7.172 ± 0.665 (mm)

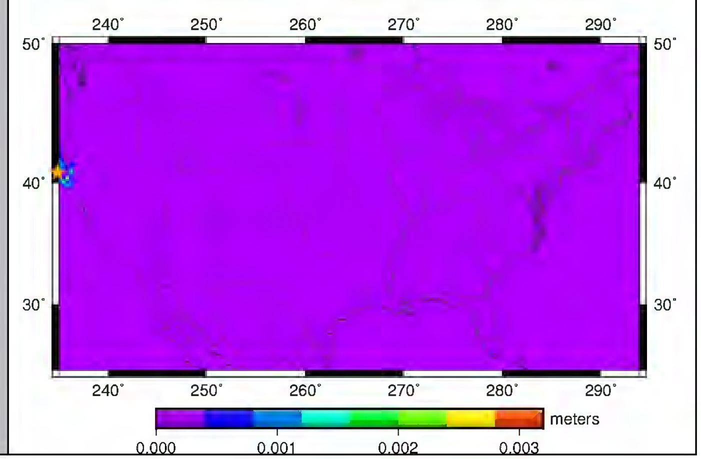
IFVM2022 v0.01 EQ shifts at epoch 2014.18691 LAT(60 sec) conus–entire total error



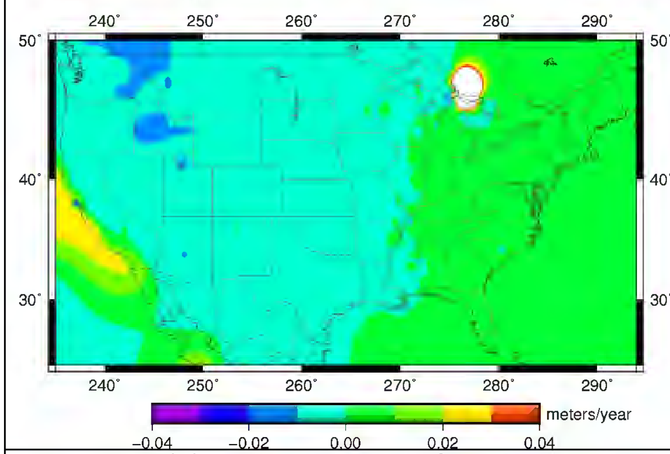
IFVM2022 v0.01 EQ shifts at epoch 2014.18691 LON(60 sec) conus–entire total error



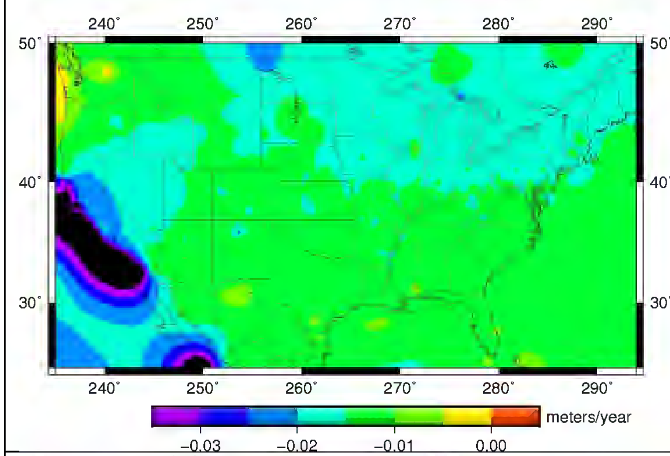
IFVM2022 v0.01 EQ shifts at epoch 2014.18691 EHT(60 sec) conus–entire total error



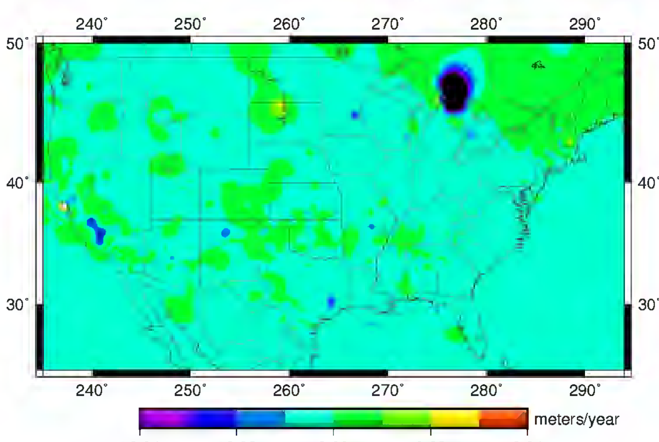
IFVM2022 v0.01 drifts from 2014.18691 to 2020.00000 LAT(300 sec) conus–entire mtcd



IFVM2022 v0.01 drifts from 2014.18691 to 2020.00000 LON(300 sec) conus–entire mtcd



IFVM2022 v0.01 drifts from 2014.18691 to 2020.00000 EHT(300 sec) conus–entire mtcd



DRIFT

From
2014.18691
To
2020.00000

Meades Ranch

$\Delta\phi/\Delta t$ = -3.427 ± 0.048 (mm/y)

$\Delta\lambda/\Delta t$ = -14.559 ± 0.093 (mm/y)

$\Delta h/\Delta t$ = -1.086 ± 0.613 (mm/y)

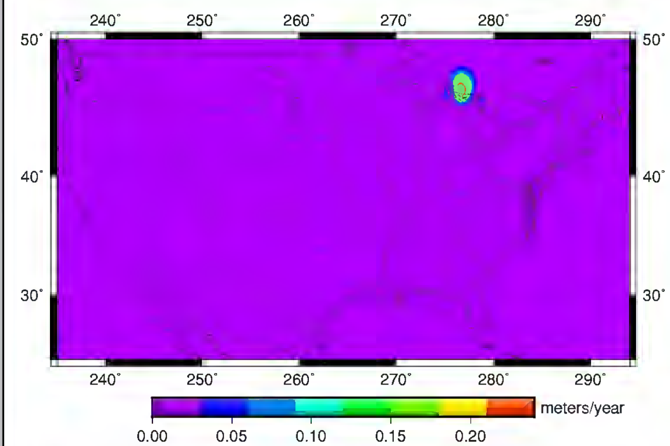
Cape Mendicino

$\Delta\phi/\Delta t$ = +18.920 ± 1.319 (mm/y)

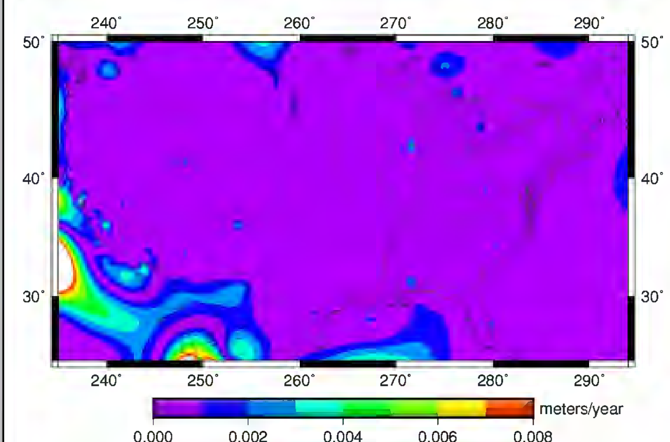
$\Delta\lambda/\Delta t$ = -19.469 ± 0.259 (mm/y)

$\Delta h/\Delta t$ = -2.353 ± 0.831 (mm/y)

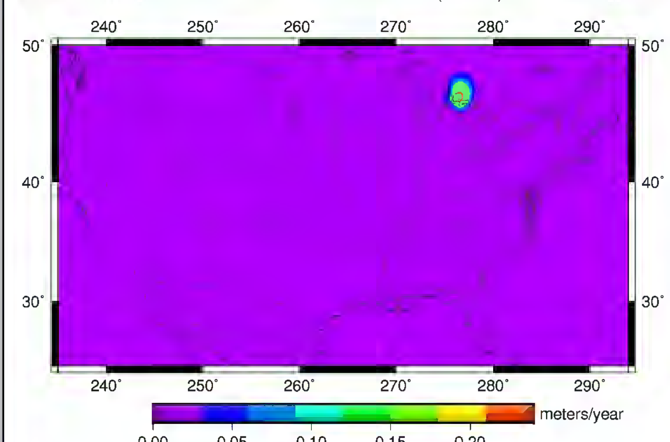
IFVM2022 v0.01 drifts from 2014.18691 to 2020.00000 LAT(300 sec) conus–entire total error



IFVM2022 v0.01 drifts from 2014.18691 to 2020.00000 LON(300 sec) conus–entire total error



IFVM2022 v0.01 drifts from 2014.18691 to 2020.00000 EHT(300 sec) conus–entire total error



The numbers above are extracted from grids, via biquadratic interpolation, but what do they mean exactly? This question will be examined in the next section.

5.1 Interpreting the interpolated values

Recall that the point of the IFVM is to provide, at a minimum, six values: At any given point, in the viable region of the IFVM, on the surface of the earth, it should provide the changes in latitude, longitude and ellipsoid height as well as the standard deviations of those three values. In this version of the IFVM, no correlations between coordinates, and no correlations between shift and drift grids were computed. As such, the total change in latitude, longitude and height are just sums of drifts over time plus shifts. The final standard deviations are derived by summing the squares of the deviations (variances) and taking the square root at the end. By way of example, consider the latitude changes at the Cape Mendocino site.

Type	Date(s)	Years	Value	Total effect	Standard deviation	variance
Drift	1995.30000 to 1999.79016	4.49016	18.472 mm/y	82.942 mm	+/- 0.961 mm/y	18.6196 mm^2
Shift	1999.79016	0	0.000 mm	0.000 mm	+/- 0.000 mm	0.0000 mm^2
Drift	1999.79016 to 2005.45238	5.55078	19.103 mm/y	106.037 mm	+/- 1.181 mm/y	42.9742 mm^2
Shift	2005.45238	0	-0.636 mm	-0.636 mm	+/- 0.070 mm	0.0049 mm^2
Drift	2005.45238 to 2010.02471	4.57233	19.116 mm/y	87.405 mm	+/- 1.217 mm/y	30.9639 mm^2
Shift	2010.02471	0	-0.005 mm	-0.005 mm	+/- 0.128 mm	0.0164 mm^2
Drift	2010.02471 to 2010.25738	0.23267	18.835 mm/y	4.382 mm	+/- 1.067 mm/y	0.0616 mm^2
Shift	2010.25738	0	0.000 mm	0.000 mm	+/- 0.000 mm	0.0000 mm^2
Drift	2010.25738 to 2014.18961	3.93223	19.245 mm/y	75.676 mm	+/- 1.355 mm/y	28.3894 mm^2
Shift	2014.18961	0	2.525 mm	2.525 mm	+/- 0.230 mm	0.0529 mm^2
Drift	2014.18961 to 2020.00000	5.81039	18.920 mm/y	109.933 mm	+/- 1.319 mm/y	58.7354 mm^2
SUM		24.7		468.259 mm		+/- 13.410 mm

Over 24.7 years, this site drifted in latitude through 6 grids, moved through 5 earthquake-based shift grids (though only 3 of the 5 had an impact), for a total movement of 468.259 mm and a standard deviation of +/- 13.410 mm. The preponderance of that uncertainty is from the application of drift uncertainty across the years. These values, out of everything else that might be derived or inferred from that grids, are the critical pieces of information which the IFVM will yield.

5.2 Comparison to geophysically constrained models

If it is not already obvious, there is an unassailable weakness in the approach taken in this study, in particular with regard to the *shift* portion. Variations in drifts can be overcome using a variety of fairly simple assumptions (such as constraining velocities at CORSs to be constant at certain parts of the plate). But a network of stations simply cannot capture the actual crustal motion of an earthquake, without additional geophysical data. A simple numerical example is presented to drive this home.

Consider the Hector Mine earthquake. Using the existing coseismic model for this earthquake (J. Saleh, personal communication), one may predict the north, east and up movements at any point. Let us pick Ludlow, California (at latitude 34.7° and longitude 243.8°, about 15 km from the epicenter. It is also about 70 km from the nearest CORS. The predicted coseismic movements, and the movements (and errors) which come from this study (based on sparse, barely moving CORSs) are shown in the table below:

Shift direction	Predicted	This study
N	-0.579 m	-0.001 m +/- 0.002 m
E	-0.090 m	-0.004 m +/- 0.002 m
U	-0.025 m	+0.001 m +/- 0.002 m

The numbers in the above table speak to the abject failure of this model in properly capturing the movement of the Hector Mine earthquake. This same check can be repeated again and again, all to the same basic conclusion: there are not enough CORSs and definitely not enough of them that move, to properly model the crustal motion of an earthquake without the assistance of additional geophysical data.

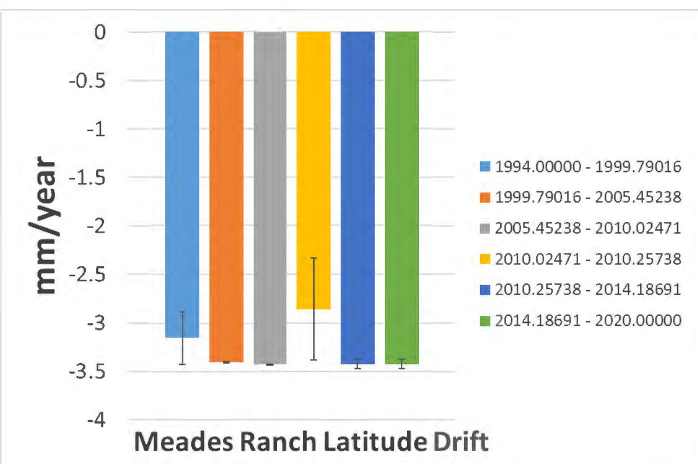
6 Conclusions

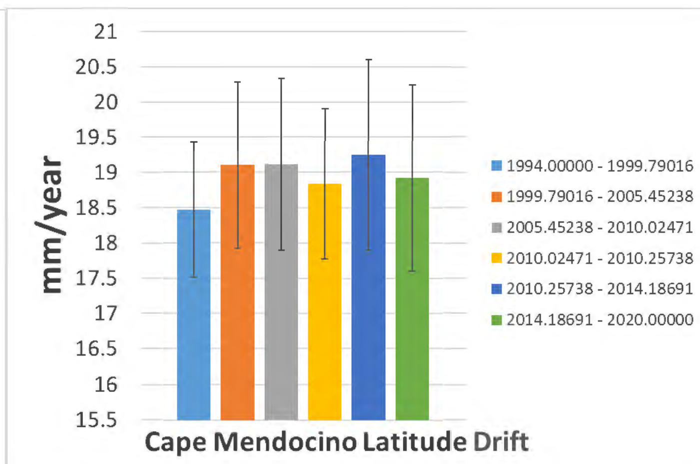
There is a wealth of information in section 5, but it isn't all immediately obvious. A summary follows, with some of the following examined in detail next:

1) Drift rates in any given drift grid can be significantly different from those in another drift grid, even in so-called "stable" parts of the plate, like Kansas
2) The extrapolation of CORS data into ocean areas makes non-land, non-CONUS values unreliable
3) Some significant inconsistency exists in CORS-based velocities in the central Great Lakes area
4) Even when extremely close to an epicenter, a CORS can remain effectively motionless (33 km from a 6.5 for 2010.0 ; 74 km from a 6.8 for 2014, and the 2014 was the one that really moved it)

6.1 Differing drift rates

Consider the drift rates in latitude for Meades Ranch and for Cape Mendicino respectively. See below.





Note that even in the heart of the so-called stable part of the North American plate, the value of latitude drift, based on the *interpolation* from surrounding CORSs is not entirely stable. The 1st and 4th drift grids vary from the other grids by a substantial amount. And yet, the error bars on those 1st and 4th drifts are huge; much larger than those of the other drifts. The exact cause of this was not investigated, but it raises a good question: should the rates of drift in an intra-frame velocity model be based upon the data of nearby stations (as was done here), or upon some sort of presumed constant tectonic rotation? Put another way: if the North American plate is truly rotating in a constant and stable way, at least for parts of the plate, why is it that looking at the velocities of stations on that stable part of the plate yields these 2 outlier drifts during these timespans?

Look next at the Cape Mendocino drifts. The variety is a bit more chaotic, but of greater interest is the large standard deviations. Part of that can be explained by a lack of data. The Cape Mendocino location is on the west coast, with no stations west of it, so that the drift rates are likely slight extrapolations from somewhat more interior CORSs. But there is also the likelihood that this location, beset as it is by earthquakes is, in fact, drifting at varying rates *between* said earthquakes.

All in all, relying purely on the interpolation of velocities at surrounding CORSs means that "stability" is not guaranteed anywhere. This can partly be chalked up to variety in what stations are chosen, leading to statistical variability in interpolated velocities. This situation also flies in the face of actual geophysical knowledge. As such, the weakness of relying upon a network of stations where some come and some go, in order to arrive at (presumably) constant velocities in the center of the continent is inherent.

More importantly, the approach in this study, of collating shift grids with drift grids, allows for each drift grid to be computed separately from the others. That is, no attempt was made to *enforce* equivalence of station velocities, across "shift grip epochs" for those stations which lie outside of the radius of expected discontinuities. This is a function of the software used, but clearly causes the problem seen above. If future work is performed along these lines, then some method of enforcing a velocity through a shift epoch, when a station is outside the radius of expected discontinuities must be adopted.

6.2 Great Lakes Issue

A glance at the error grids in chapter 5 shows that in both latitude and ellipsoid height, there is something significantly wrong at the Mackinac area of Michigan. To help discuss this, we note that two sources of error contribute to the error grids: method noise and data noise. The method noise is the variation which arises if the actual IFVM grids are created with different tensions. Data noise is a measure of how well the created grid actually agrees with the input data. Since the grid is made from a thinned (block-median filtered) data set, the data noise is a measure of how well the grid recreates *all* of the input data, not just the thinned data. While the exact culprit (station or stations) hasn't been tracked down, it is clear that the reason the error grids are large is due to data noise. That is, we seem to have stations drifting at radically different rates in latitude and ellipsoid height, very near one another, in the Mackinac region. The plot below is the most convincing evidence:

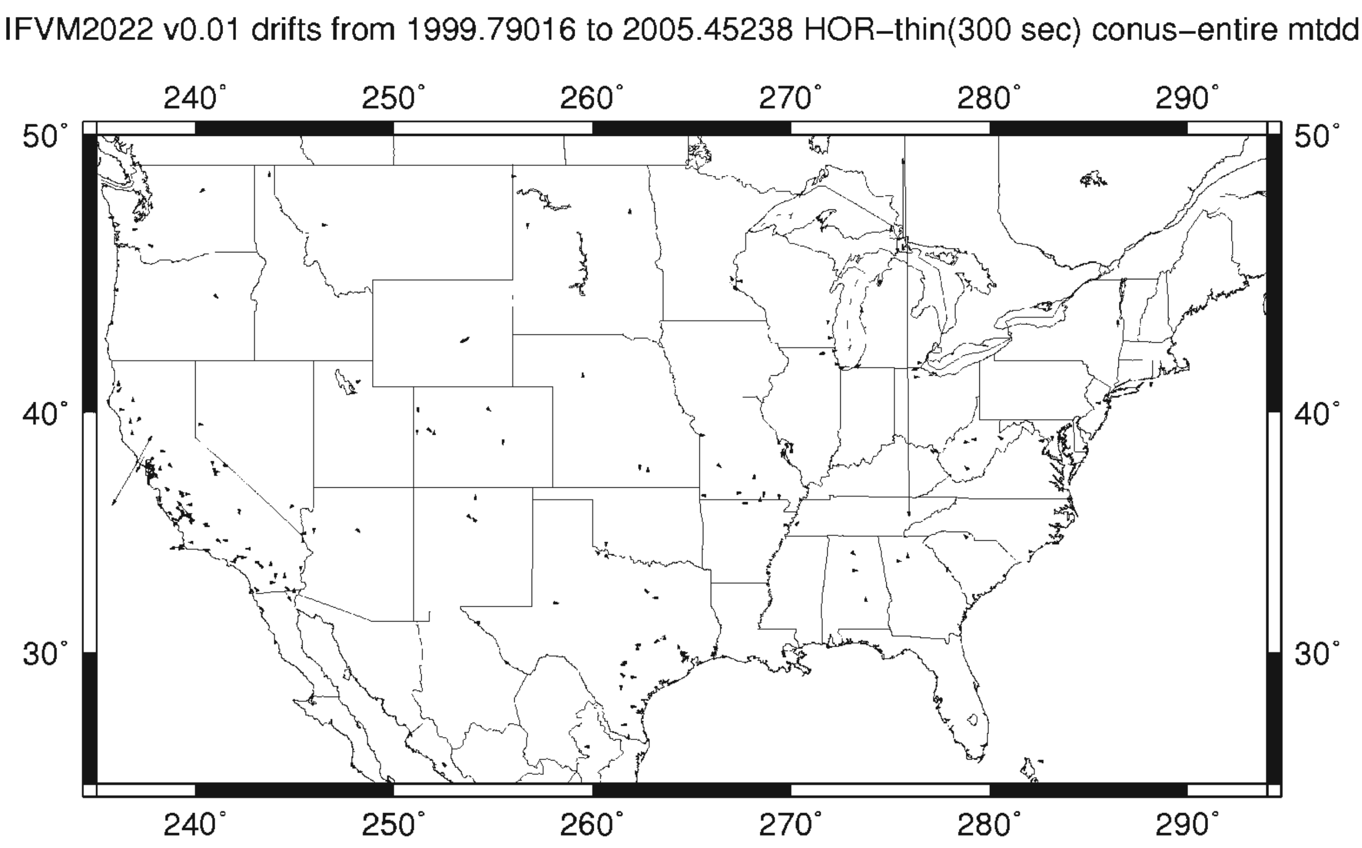


Figure 26: Horizontal drift residuals between input data and grid

This plot shows the residuals between what the grid says are the horizontal movements and what the actual stations say are the horizontal movements, for the time period between 1999.79016 and 2005.45238. Note that most movements are so small as to appear just as arrowheads. But there are large vectors pointing north and south in Mackinac. That means that the grid (based on the block-median thinned input data) disagrees in a north/south rate with (it looks like) 3 different stations in that region. Note it is almost entirely a N/S disagreement, which would explain why the error grid in longitude does not show this same feature that is shown in latitude. A similar issue must be happening in the ellipsoid heights.

A deeper analysis of this region in particular will be done based on this, but for now, the statistics of the IFVM are telling the whole story – the grid yields up a smooth motion (due to block-median filtering), but the uncertainties in that movement are large in Mackinac due to the variety of motions of all the stations in that region, especially in latitude and ellipsoid height.

6.3 Magnitudes of shifts and their errors

As mentioned earlier, the largest shift seen in a brief discontinuity between 1996 and 2017 at any CORS in the NCN or IGS network was 10.2 cm. That fact alone should be seen as highly informative as to the general inability of CORS-only data sets to adequately capture earthquake shifts. This is not to say that the shifts are wrong. There is no reason to believe they are, considering the correlation in time between discontinuities and "nearby CORSs" as in Table 4.

As the shifts themselves are too small, so too must (in the method adopted) be their error estimates. In the gridding algorithm adopted (which was statistically meaningful for NADCON 5, see Smith and Bilich (2017)), the only two pieces of information contributing to error estimates were:

1) Method noise (representing the flexibility of the interpolated surface to tension chosen)
2) Data noise (representing the agreement of nearby points to one another)

In neither case would small (generally millimeters) shifts be expected to yield error estimates that were larger than millimeters themselves. Thus, while these numbers do indicate what they were designed to indicate, the fact that the stations themselves did not fully capture the shift signal of an earthquake meant that the error estimates are also as meaningless as the shift themselves.

6.4 Variability in drifts

It was interesting to learn that, for any given "drift grid", the drift at some randomly chosen location (not at a CORS) could have such variation in interpolated drift velocities. This appears to be an artifact of the "collated" approach, where each drift grid is computed separately from the others, allowing for different stations to contribute or not contribute to the interpolated velocity at some point. In the future, whether it be with a CORS-only approach or something more refined, this collation should be abandoned. Consider the figure below. In the future, point B, falling outside the radius of expected discontinuities (green circle) should have its velocity in drift grid 1 and drift grid 2 enforced to be identical in each. Contrast that with point A which could justifiably have a pre-shift and post-shift velocity computed independently (as well as a shift for the shift grid.)

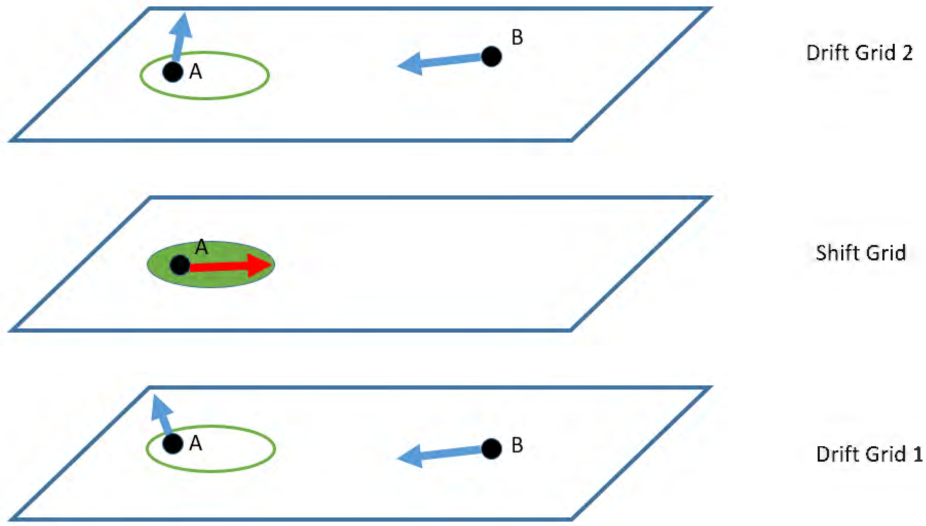


Figure 27: Future work, enforcing velocities at grid node "B" across a shift grid

7 Summary: failure versus success

Depending upon the lens through which you read this paper, it was either a failure or a success.

On the one hand, the vast quantity of data available at NGS at the NCN and IGS Network stations makes it tempting to wonder whether crustal motion can be tracked at those stations at high accuracy and low cost. This is especially so in CONUS where over 2000 stations have existed in the NCN history, nearly 2000 are active today, and the most expansive plans being considered for the network call for as many as 10,000 active stations. This can (and did) lead some within NGS to expect that at least a moderately viable Intra-Frame Velocity Model could be created solely from well-determined coordinate functions at CORSs. Considering NGS's future plans to work more closely with the ever-growing RTN community, the temptation to rely solely upon GNSS stations as cheap, continuous data sources increases.

On the other hand, station locations are chosen (almost to a fault[8]) to be in stable areas with an expectation that they will not be affected by extraneous movements besides those of simple tectonic drift. This means that when earthquakes happen, they tend *not* to affect CORSs as much as other things on the crust of the Earth. This should, but did not, have put an expectation that tectonic drift might be well determined, but episodic changes would be poorly modeled.

So, from an "expectation" lens, this study can be called a failure. It failed to provide all of the IFVM information that NGS would need to accurately model passive mark movements through time, especially including motions due to earthquakes, without additional information.

However from an "information gained" lens, this study can be called a success. It showed that tectonic drift is well determined from CORSs (but also pointing out that that there is variability coming from interpolation errors based upon a changing set of stations on either side of shift grids). The study even showed some coherence between CORS-based brief discontinuities and earthquakes, but that the magnitudes of those shifts are simply inadequate for anything like realistic earthquake modeling. It showed that NGS must dedicate additional resources to studying non-CORS-based ways to fully understand earthquake motions, if they wish for an IFVM to accurately reflect true motions of the crust.

There is one other conclusion that cannot be determined from this study, but which is coming next: will the CORS-only IFVM created in this study serve as an adequate set of prior information for the least squares adjustment models which

[8] No pun intended

will be used to create Final Discrete Coordinates (FDCs) and especially Reference Epoch Coordinates (RECs)? This question could be posed for “near earthquake” and “far from earthquake” stations, separately.

That, ultimately, was the reason this study was initiated. In fact, that is the reason the IFVM is being pursued *at all* by NGS. As a reminder, it is not the mission of NGS to understand the motions of all points on the crust (whether they be empty plots of land or passive geodetic control points) through time. Only if a geodetic control point is tracked continuously (such as with a CORS) can we do that. But we can estimate passive mark locations at different epochs using what limited (episodic) survey data we have.

Focus on that key word: ***estimate***

The estimation of a passive mark’s coordinates at some epoch different from when the mark was actually surveyed requires some estimate of what the crust was doing at that point, through the time between being surveyed and the epoch at which we are attempting to estimate coordinates. It is possible that the IFVM created in this study will be good enough to allow those estimates to be made with estimated uncertainties which reflect all error sources. After all, NGS has been clear: if you want to know the most accurate coordinates on a passive control point, do *not* rely upon transformation tools or estimation techniques which “move” old survey data through time. Rather, your best bet is to get out to the passive mark and (re-)survey it. Or, better yet, rely upon the NCN, whose coordinate estimates in the future will be monitored day in and day out, and if you can avoid it, don’t rely upon passive control at all.

8 References

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