White Paper

Deformation models in Trimble Access 2020.20 and Trimble Business Center 5.40

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Introduction

Due to the effect of plate tectonic motions, the actual positions of points on the earth change continuously and this is reflected in global datums such as the International Terrestrial Reference Frame (ITRF), where coordinates change continuously with time. This is particularly important with the advent of precise Point Positioning (PPP) services like Trimble RTX® correction services, which provide coordinates in the ITRF at the epoch of measurement. However nearly all users find it difficult to deal with continuous coordinate change, so national datums have coordinates that are static. By modeling the motion of the earth's surface, these national datums project each coordinate to its position at a common date called the reference epoch, while still providing a link to the global systems. Accurately transforming coordinates from a global datum to a national datum is a non-trivial task, and Trimble® has made significant enhancements to key software packages, automating this task for its users.

Semi-dynamic datums

Modern semi-dynamic datums are usually based on a version of the International Terrestrial Reference Frame. Stable coordinates are produced by projecting each coordinate to its position at a common date called the reference epoch. To make this technique work, we need a model of how the earth is moving due to plate tectonics. In stable areas, the effect of earthquakes will be small. The motion of the points will follow the motion of the tectonic plates and can be calculated using Euler Poles. Indeed, in some countries (such as Australia) these are incorporated in 14-parameter datum transformation equations, and no further corrections are necessary to provide stable coordinates. However, for a country like the US where part of the country lies across a plate boundary, a different strategy must be adopted. In this case an Euler Pole may be adopted to take care of the deformation in the stable part of the country, and a deformation model is used for residual deformation, particularly in the plate boundary zone. Coordinates are propagated to a standard epoch (2010 in the US for example) using a numerical model of deformation across the plate boundary. These models contain separate models of the secular (continuous) velocity field associated with on-going deep-seated tectonic processes and displacements associated with significant earthquakes. Other (smaller) effects, like post seismic relaxation that sometimes occurs after large earthquakes, are also included in some cases. The models are shown schematically in Figure 1. Note that the effect of earthquakes is an instantaneous offset while the effect of the velocity increases linearly with time. The total motion is just the sum of the earthquake and constant velocity terms.

Deformation models now supported in the Trimble Geodetic Library

The Trimble Geodetic Library (TGL) underlying both Trimble Access™ software and Trimble Business Center™ (TBC) software has been recently upgraded to support semi-dynamic datums. This requires that TGL support time-dependent datum transformations (introduced with Trimble Access 2020.00 and TBC 5.30) and deformation models (introduced with Trimble Access 2020.20 and TBC 5.40).

- The support for time-dependent datum transformations is an enhancement to allow TGL to transform coordinates more accurately than was possible in the past. It also allows us to support plate-fixed datums like NAD83 and the upcoming reference frames NATREF2022, PATRF2022, MATRF2022 and CATRF2022.

- Our support for deformation models allows TGL to develop accurate coordinates in tectonically active areas. In practice both the velocity and earthquake shifts are stored as a series of grid files, which are used to estimate the appropriate values for an arbitrary point by linear interpolation. The basic idea of a National Deformation Model is illustrated in Figure 1, which shows the trajectory of a point affected by a constant velocity and two earthquake shifts which are combined to estimate the total displacement. These are then used to correct the coordinates back to the reference epoch. In addition, the models can also correct for post-seismic deformation.

The correction equation is:

$$m_k(t,\theta,\varphi) = v(\theta,\varphi)_k t + E(\theta,\varphi)_{ki} H(t-t_i) + P(\theta,\varphi)_{ki} H(t-t_i)\left(1 - e^{-\frac{(t-t_i)}{tc_i}}\right)$$

Equation 1

- Where m is the displacement
- v is the velocity (ndm)
- E is the earthquake shift (patch)
- P post-seismic decay
- H is the step function

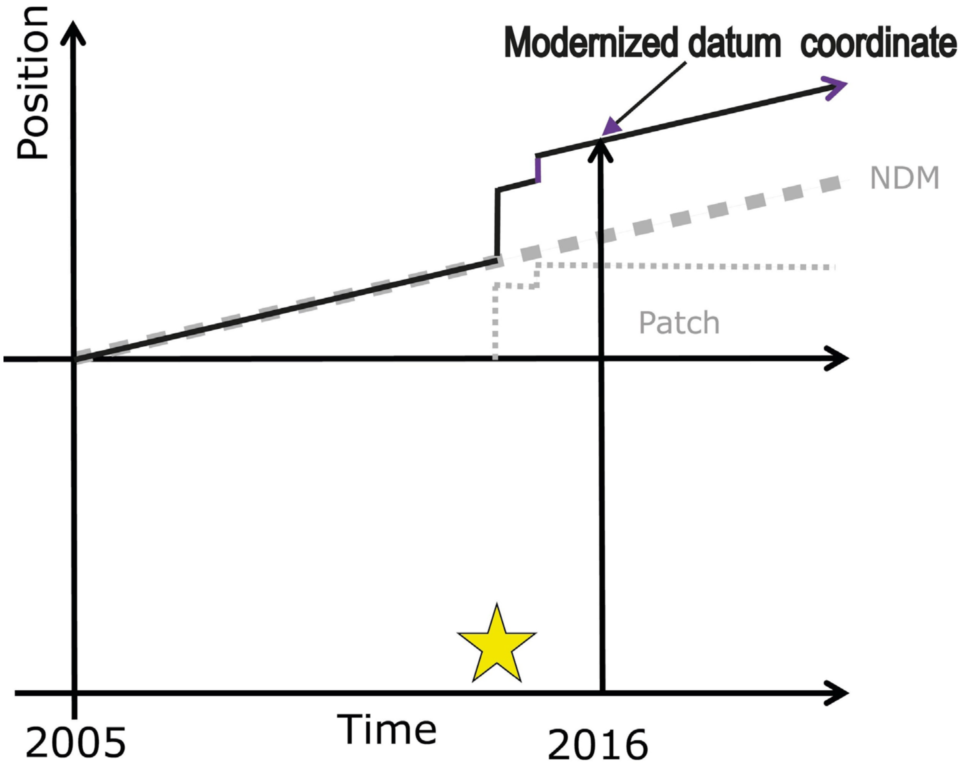

Figure 1 Schematic diagram of a dynamic datum. Heavy dashed gray line shows the secular velocity. Yellow star indicates an earthquake. Thin gray dotted line co-seismic contribution the deformation model. The solid black line shows the deformation model with both contributions combined

NAD83 deformation models

As an example, consider the North American Datum of 1983 (NAD83). The National Geodetic Survey (NGS) is a federal agency responsible for maintaining NAD83 in the United States. The NGS provides a Horizontal Time-Dependent Positioning (HTDP) utility for transforming coordinates. From December 2020, TGL supports the time transformation functions that HTDP uses to correct positions to 2010 (the reference epoch NAD83 2011) by supporting the same velocity models and earthquake models that HTDP uses.

Velocity grids

The extent of the velocity grids for Alaska and CONUS are shown in Figure 2. Note that the grids for Alaska and CONUS do not overlap. For this reason, these models are treated as separate models in TGL These models only support time corrections to the reference epoch of NAD83(2011) and the observation time must be after 2010.0.

Figure 2 Alaska and CONUS velocity grids

Both the Alaska and CONUS models consist of a main velocity grid that covers the full extent of the model, which both have a grid spacing of 0.25 ° in both latitude and longitude. In addition to the main grid, the CONUS model has four subsidiary grids with a finer grid spacing along the west coast where the tectonic activity is concentrated. These are the Pacific Northwest (PNW), Northern California (NC), and Southern California (SC), which all have a grid spacing of 0.0625 °, and the Creeping San Andreas (CSA) with a grid spacing of 0.01 °. The CSA grid covers the area where the section of the San Andreas Fault is creeping to the surface and thus produces a very sudden velocity change across the region when the fault is crossed.

Earthquake Grids

HTDP contains models for 28 earthquakes. However only one of these, the 4 April 2010 Sierra El Mayor Earthquake, occurred after the 2010 reference epoch of NAD83(CONUS), so this is the only Earthquake patch we have included in our CONUS deformation model. This patch is labelled SEM CS in Figure 2. In addition, the 2002 Denali (M=7.9) earthquake is still producing measurable post-seismic deformation so we have included a post-seismic model in the Alaska deformation model.

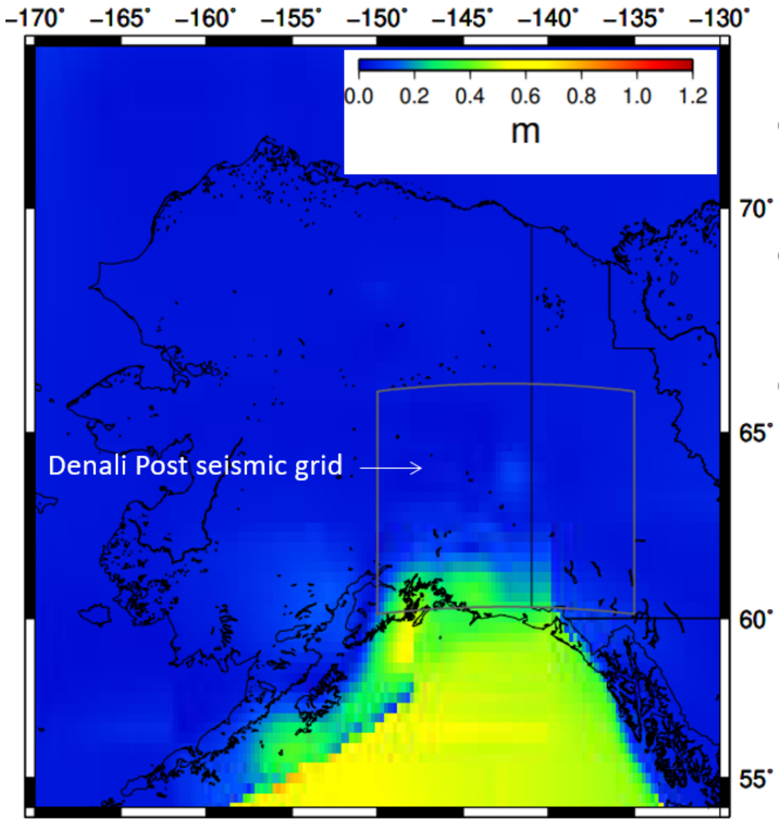

Figure 3 Predicted displacements 2019-2010 for Alaska in the NAD83 datum.
The boundary of the Denali post-seismic grid is outlined in grey.

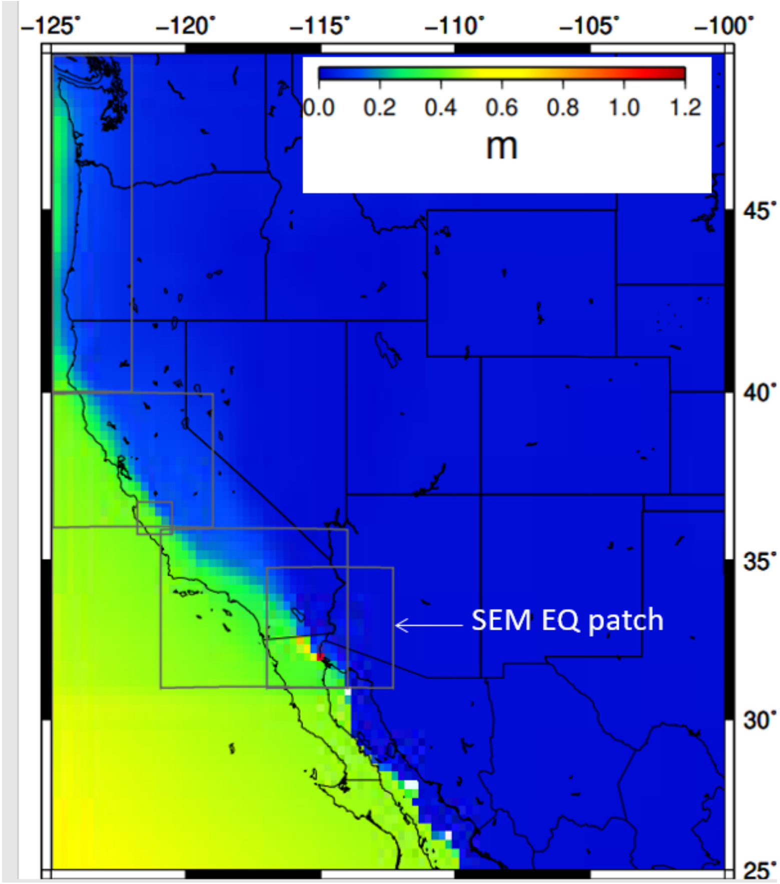

Figure 4 predicted displacements between 2010.0 and 2019.0 relative to NAD83. The boundaries of the velocity sub-grids and the Sierra El Mayor Earthquake patch are outlined in grey.

The figures above show the displacements that the deformation models predict between the 2010.0 and 2019.0 for Alaska (Figure 3) and CONUS (Figure 4). These represent the corrections that the Trimble Geodetic Libraries will apply to RTX coordinates measured in 2019 to account for deformation between 2019 (the epoch of measurement) and the 2010.0 reference epoch of NAD83(2011). Clearly the significant distortions (>0.2m) are restricted to a narrow zone along the coast. In CONUS these are mostly in California and the large distortions of up to 1 m are caused by the 2010 Sierra El Mayor Earthquake.

Test results of TGL implementation

We tested the TGL implementation by taking RINEX files for 68 GNSS stations in CONUS (see Figure 5). We submitted all of these files to OPUS and then extracted ITRF epoch of measurement (eom) and NAD83(2011). The ITRF coordinates were converted to NAD83 using the standard ITRF2014-NAD83 14-parameter transformation, and then corrected back to epoch 2010 using our implementation of the velocity and earthquake models in HTDP to get NAD83(2011) coordinates. We then compared the NAD83 coordinates derived from the ITRF2014 eom coordinates with those from HTDP, which we have treated as truth.

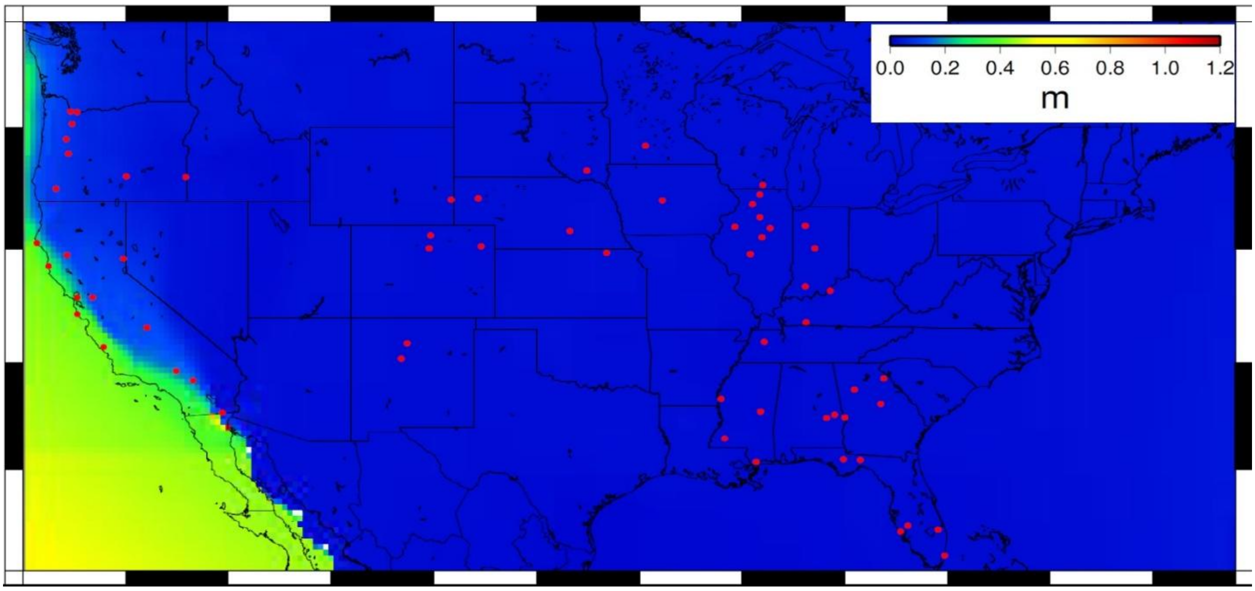

Figure 5 Location of test points shown by red dots. Color scale shows the total between 2010.0 and 2019.0 relative to NAD83.

By comparing our NAD83 coordinates with the NGS derived “truth” values we developed residuals in the e, n and u directions. The residuals are summarized in the following table:

	e m	n m	u m
Max	0.0045	0.0013	0.0010
Min	-0.0032	-0.0008	-0.0011
Mean	0.0003	0.0002	0.0000
Standard Deviation	0.0014	0.0005	0.0005

The implementation of the HTDP deformation models match the NGS values with a standard deviation of less than 1.5 mm in the e, n and up direction with the greatest residuals in the east direction.

Boots on the ground

The real test of our implementation is how it performs in the field. To check this, we selected 4 NGS control points in California and 29 in Colorado. We downloaded the NGS data sheet for each control point to act as truth. We measured the points with a Trimble R12 receiver using Trimble Access 2020.20. Measurements were 180 second RTX Observed Control Points with the receiver set up on a bipod.

We then imported the data into Trimble Business Center 5.40. The Grid coordinates reported by Trimble Access / TBC were compared to the State Plane coordinates from the NGS data sheets.

As an example, consider AA1871, a height modernization point in San Antonio, California.

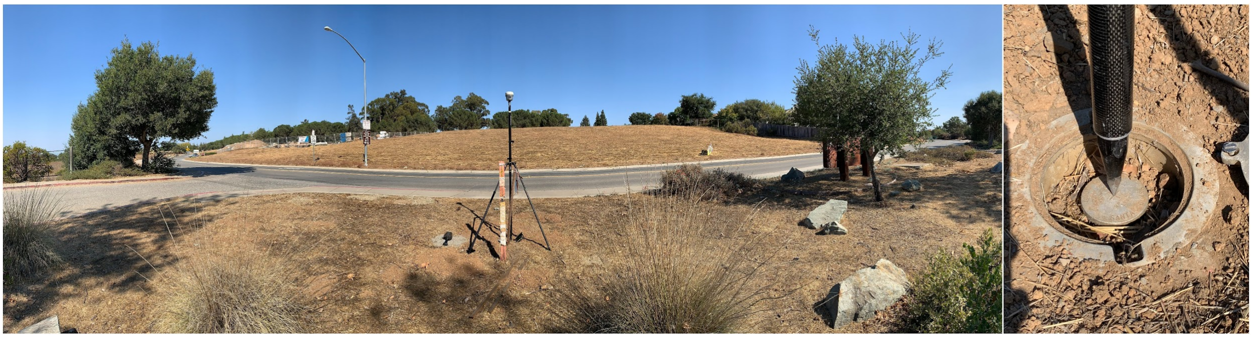

Figure 6 Setup at NGS control point AA1871 in San Antonio, California.

```
AA1871  DESIGNATION -  HPGN D CA SAN ANTONIO
AA1871  PID         -  AA1871
AA1871  STATE/COUNTY-  CA/SANTA CLARA
AA1871  COUNTRY     -  US
AA1871  USGS QUAD   -  CUPERTINO (2018)
AA1871
AA1871                         *CURRENT SURVEY CONTROL
AA1871  ______________________________________________________________________
AA1871* NAD 83(2011) POSITION- 37 19 52.98965(N) 122 04 59.33665(W)   ADJUSTED
AA1871* NAD 83(2011) ELLIP HT-   100.120 (meters)        (06/27/12)   ADJUSTED
AA1871* NAD 83(2011) EPOCH   -  2010.00
AA1871  GEOID HEIGHT    -        -32.596 (meters)                     GEOID18
AA1871
AA1871. The following values were computed from the NAD 83(2011) position.
AA1871
AA1871;                    North         East     Units Scale Factor Converg.
AA1871;SPC CA 3     -   593,454.608 1,859,708.053   MT  0.99995584   -0 58 09.3
AA1871;SPC CA 3     - 1,947,025.66  6,101,392.17   sFT  0.99995584   -0 58 09.3
```

Figure 7 NGS data sheet for point AA1871

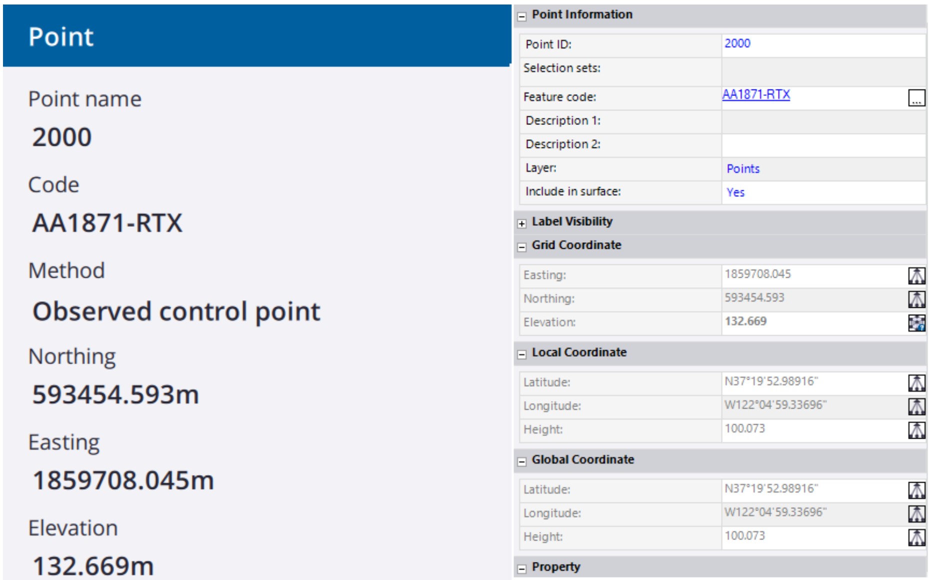

Figure 8 Point AA1871 as-measured in Trimble Access and in Trimble Business Center

Importing the NGS datasheet into Trimble Business Center we get an elevation of 100.120 + 32.596 = 132.716m.

Comparing the NGS datasheet coordinates with those from the RTX observed control point we get:

	East (m)	North (m)	Elevation (m)
NGS data sheet	1859708.053	593454.608	132.72
RTX observed control point	1859708.045	593454.593	132.669
Difference	0.008	0.015	0.047

Summary results from the 4 points in California are:

	East (m)	North (m)	Elevation (m)
Max	0.017	0.017	0.066
Min	-0.015	-0.008	-0.020
Mean	-0.002	0.009	0.035
Standard Deviation	0.014	0.011	0.038

For the 29 points in Colorado:

	East (m)	North (m)	Elevation (m)
Max	0.033	0.016	0.064
Min	-0.024	-0.077	-0.120
Mean	-0.002	-0.005	-0.011
Standard Deviation	0.013	0.020	0.046

These results include errors from all sources: GNSS positioning error, time dependent transformation error, mark disturbance and local subsidence. The results demonstrate that with the support for the HTDP deformation model in Trimble Access 2020.20 and TBC 5.40, RTX is a highly effective means of getting NAD83 (2011) positions.

Support for deformations in other countries

Deformation models are increasingly incorporated in national datums for countries located on the boundaries of tectonic plates. Currently Trimble supports deformation models for 10 countries:

Country	Reference frame	Local displacement model
Brazil	SIRGAS2000	VEMOS2009
Denmark	EUREF-DK94	NKG-RF03
Estonia	EST97	NKG-RF03
Finland	EUREF-FIN	NKG-RF03
Sweden	SWEREF99	NKG-RF03
Norway	EUREF89	NKG-RF03
Iceland	ISN2016	ISN2016
New Zealand	NZGD2000	NZGD2000 Deformation Model
USA	NAD83(2011)	HTDP V3.2.9
Canada	NAD83(CSRS)v7	CSRS Velocity Grid V7.0

For most of these countries the deformation models only include a velocity grid. This includes the NKG-RF03 for the Nordic Countries, ISN2016 for Iceland, the CSRS Velocity Grid V7.0 for Canada and VEMOS2009 for Brazil. Two of the countries listed in Table 2 have deformation models that incorporate earthquakes. In the USA as described above, only one of the earthquakes occurred since 1 Jan 2010(the reference epoch of NAF83(2011) and that is included as an earthquake patch. For New Zealand, the situation is more complex. New Zealand has had numerous earthquakes since 1 Jan 2000 (the reference epoch of NZGD2000) however the coordinates in NZGD2000 are retrospectively adjusted to correct for the earthquake shifts through a technique of reverse patches (Crook et al 2016), which means we do not need to apply earthquake patches for most of the New Zealand earthquakes in our implementation. As a result we only have to implement eight grids associated with the post seismic effects of the M7.8 Kaikoura earthquake of 14 November 2016.

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