Map Datums

In the days of navigation only from paper maps, most of us knew (and needed to know) little about datums. But with the advent of GPS receivers and mapping apps on smartphones we need to know more about datums to avoid going astray.

A datum is a point, or a network of points from which distances and directions to other locations can be specified (a reference frame). A modern geodetic datum uses an ellipsoid to model the shape of the earth, and an origin (the centre of the earth's mass in a geocentric datum). Then a 3D coordinate system (eg lat ϕ - lon λ - height h) can be used to describe locations near the earth's surface. Many reference frames exist, and they may give different grid coordinates for the same location https://epsg.io/about. It gets a bit complicated when we want to project the curved surface of the earth onto flat maps (be they on paper or a screen). There are various map projections with different merits for particular uses, and corresponding coordinate systems in 2D and in 3D (for contours and spot heights). Coordinate systems are sometimes either called datums or given the same name {eg from the GDA2020 Technical Manual: Ellipsoid = GRS80; Geodetic Datum = GDA2020; Geographic/Ellipsoidal Coordinate Set (degrees) = GDA2020; UTM Projection Grid Coordinate Set (metres) = MGA2020}. Experts may distinguish between the underlying ellipsoid, the datum, the projections, and the coordinate systems used with them.

In 1994, the GDA94 datum was very close to WGS84 used by default in most Global Positioning System / Global Navigation Satellite System (GPS/GNSS) receivers. However, because of continental drift and local changes in the earth surface, positions determined using WGS84 may now be a few meters out in relation to locations of features displayed on a GDA94 map. The features have moved while the GPS 'grid' has not. A new national map datum is generally an attempt to restore the alignment between coordinates of surface features from official maps and GNSS (at a nominated date). Lat-lon and UTM coordinates are both affected, because UTM is a system for projection of the curved earth surface onto a flat map.

GDA2020 (like GDA94) is a "plate-fixed" datum (linked to surface reference stations at a specified epoch). So reference locations change slowly with time relative to an "earth-fixed" datum such as WGS84 (a static grid on an ellipsoid around the centre of the earth's mass, around which the navigation satellites orbit). Users are sometimes confused when a plate-fixed datum is called "static" whereas an earth-fixed datum is called "dynamic". These designations only make sense from the perspective of a location that appears by local observation to be "static" on the earth surface, though in reality that location is slowly moving due to tectonic plate drift. A "plate-fixed" datum assigns static coordinates for locations on the Earth's dynamic surface, but as the plate drifts these coordinates will gradually move away from those determined using an "earth-fixed" datum in a GPSr at the same location.

At very high resolution the situation is more complex because WGS84 as a GNSS datum (EPSG:1156-datum, EPSG:1309-datum, etc) is recalculated for improved precision on a world-wide basis twice a year (WGS revisions are numbered like G2296); whereas WGS84 as used for web mapping (EPSG:6326-datum, EPSG:4326-geodetic cs and EPSG:3857-projected cs) is commonly not updated. In practice, the difference is only a few centimetres. However, when transformations are involved (eg from GDA coordinates) the calculated WGS locations may have an error up to 3 m.

The Australian continent is drifting NNE by about 7 cm each year. In GDA2020, coordinates in Australia are roughly 1.8 m NNE of those in GDA94 (26 y * 0.07 m/y = 1.82 m). In January 2020, GDA2020 matched WGS84 (which matched ITRF2014); and they diverge horizontally by about 7 cm each year. Within a bushwalker's lifetime the difference between GDA2020- and WGS84-

measured coordinates may be a few meters, or about the typical resolution of an affordable GPS device. Looked at another way, with a paper map at a scale of 1:10,000 a change in coordinates of 1.8 m (from GDA94 to GDA2020) would equate to a displacement on the paper map of 0.18 mm (essentially undetectable). The change is indistinguishable in a 1:25,000 GeoPDF (but new generations of the map may be vastly improved in other ways - look on the map server to check). The difference is observable in some high-resolution products eg Nearmap. In the future, the official datum for Australia may change to an "earth–fixed" reference frame such as ATRF2014 and the date will be an integral component of the coordinates for a surface feature.

There were much bigger changes from older map datums like AGD66 (about 200 m NE to GDA94), because these were based on spheroids (ellipsoids that do not allow for flattening at the poles) and projections which were later refined through improved understanding of the earth shape. Unlike GDA and WGS, they were not geocentric, and the grid did not necessarily match those used in other countries. Over time, preferred projections, coordinate systems, grid systems and calculation methods have also changed. Even the Universal Transverse Mercator (UTM) system has evolved, but the current version has been widely used for many decades.

The projection used in Australian topographic map sheets varies depending on several factors (especially scale and intended use). Unfortunately it is not always specified (likely in metadata for electronic map sheets). Australian 1:25000 topographic maps generally use a UTM reference grid system on a Transverse Mercator map projection using the same central meridian. This is a conformal projection, so directions at any point (and shapes) are correct, but distances and areas will have errors (small within any 1:25,000 map sheet). No projection of a curved surface onto a flat plane can preserve both angles and distances. Distortion within a UTM zone is < 0.1%. Further distortions of paper maps come from folding and humidity change, but the sum of these errors is unlikely to trouble a walker who takes clues from the surrounding topology. Take care, because a map with a valid datum and projection can still have geo-referencing errors, eg the 2016 geopdf maps from nsw.spatial. Things get complicated with 'slippy' tiled maps, which may use variations on spherical Mercator (a grid square is wider on screen in the S of the nsw.spatial Topo mosaic).

The central repository for geographic reference and translation systems is EPSG. There can be confusion because in EPSG the same number can apply to a datum and an unrelated projection, coordinate system and/or transformation. We should really use a name like "EPSG:1168 Geodetic Datum" to avoid such confusion.

Key (horizontal) coordinate systems (cs) likely to be encountered by Australian bushwalkers in 2024 (● Ellipsoidal:YX-degrees, ○ Projected:XY-metres) are:

- WGS84 (datum EPSG:6326, equivalent to ITRF, earth-fixed) cs - EPSG:4326
  - WGS84 Spherical Mercator (EPSG:3857)
- GDA94 (datum EPSG:6283) geographic cs (plate-fixed, matching WGS84 in epoch 1994) - EPSG:4283
  - GDA94/MGA UTM Zones 49-56 (EPSG:28349 - EPSG:28356)
- GDA2020 (datum EPSG:1168) geographic cs (plate-fixed, matching WGS84 in epoch 2020) - EPSG:7844
  - GDA2020/MGA UTM Zones 49-56 (EPSG:7849 - EPSG:7856)

In theory, apps like OruxMaps (OM) that can display maps from various sources check the datum in metadata when map files are loaded, and warn of unsupported projections. They may not be accurate at this if: (i) the app is unaware of some new datum, or (ii) the app has inaccurate settings for a datum, or (iii) there is some other error in the map file or the app. So when different maps are compared, the same feature on the earth surface sometimes appears in a slightly different place (in relation to a UTM grid for example). OM seems safest with WGS84 (which is still used in WMTS from nsw.spatial at least). Geopdfs and geotifs based on other datums (notably GDA2020) seem prone to errors in OM. The TerraGo Toolbar may report an older datum without warning (eg GDA94 for a map created using GDA2020).

Heights specified from GPS systems are generally given in relation to the ellipsoid / spheroid (not the national height datum), and are notoriously inaccurate when few satellites are available. But heights (including contours) on printed maps are generally given in relation to the geoid, a shape determined by gravimetric measurement, approximately the surface that the oceans would make if canals criss-crossed the land masses. Water flows with gravity, not the ellipsoid. To complicate matters, some GPS receivers silently calculate geoidal heights. Barometric estimation assumes that the pressure drops at a standard rate as altitude is gained above mean sea level, but changing conditions mean that estimates can be up to 10% different from GPS systems, even with temperature correction. Ellipsoidal heights differ by about 0.1 m (practically unchanged) between GDA94 and GDA2020. The Australian Height Datum (AHD) is based on a network of points benchmarked by gravimetric measurements relative to mean oceanic sea level around 1970. It is close to the geoid and varies from ellipsoid height by between -30 and +70 m. Various sources of DEM data may use different arbitrary reference levels for both spot heights and contours (often specified as mean sea level, which is probably the same as geoid level). SRTM used the EGM96 height datum which differs from AHD by -0.8 m to 1.2 m (generally less than uncertainty in the SRTM heights). Even in 1 arc second DEMs after correction for vegetation, errors relative to LIDAR measurements may exceed 50 m. Other height datums exist to meet various needs (eg mariners and flood rescue workers). In the future, the official height datum for Australia may change to AVWS, which allows more precise alignment to heights measured using orbiting satellites.

A fuller list of EPSG codes relevant to Australian hikers is:

6283 = GDA94 Geodetic (and Geocentric) Datum.
4939 = GDA94 Geographic/Ellipsoidal 3D cs (angles in degrees & ht in metres).
4283 = GDA94 Geographic Horizontal 2D cs (angles in degrees; traditionally YX latϕ-lonλ but sometimes XY λϕ).
28349 to 28356 = GDA94 UTM Cartesian Horizontal 2D cs for MGA zone 49 through MGA zone 56;
Projected: UTM (distances in XY metres: {false, ie offset to avoid negatives} Easting then Northing, in a zone).

1168 = GDA2020 Geodetic (and Geocentric) Datum.
7843 = GDA2020 Geographic/Ellipsoidal 3D cs (YX degrees & Z ht).
7844 = GDA2020 Geographic Horizontal 2D cs (YX degrees).
7842 = GDA2020 Geocentric Cartesian 3D cs (XYZ metres). I have not seen 7842 or 7845 used.
7845 = GDA2020 Geocentric Cartesian 2D cs; Projected : Lambert Conic Conformal(XY metres).
7849 to 7856 = GDA2020 UTM Cartesian Horizontal 2D cs for MGA zone 49 through MGA zone 56;
Projected: UTM (XY metres): {false, ie offset to avoid negatives} Easting then Northing, in a zone).

4327 = WGS84 Geographic/Ellipsoidal 3D cs (YX degrees & Z ht). Deprecated?
4326 = WGS84 Geographic Horizontal 2D cs (YX degrees).
3857 = WGS84 Cartesian 2D cs Projected: Pseudo- / Spherical Mercator (XY metres, with a global origin different from UTM zones).

9000 = ITRF2014 Ellipsoidal Horizontal 2D CS (YX degrees). The previous basis for WGS84-EPSG:4326?
9990 = ITRF2020 Ellipsoidal Horizontal 2D CS (YX degrees). The current basis for WGS84-EPSG:4326?

7019 = GRS1980 Ellipsoid (also called GRS80). Used by all of the above.

5111 = AHD a gravimetric model close to the geoid (a surface like average sea level if a grid of canals criss-crossed the continent).
5711 = height above AHD, more easily calculated from local ground surveys.
1292 = AVWS, an improved gravimetric model, especially over larger areas (> 10 km).
9458 = height above AVWS, more easily calculated from distance to orbiting satellites.

There are also compound reference systems, eg
9463 = GDA2020 + AHD height.

In GDA coordinate systems, the term the term **Geographic** (Ellipsoidal) means specified in latitude (Y angle) and longitude (X angle) from the ellipsoid centre, and if 3D height (distance above the ellipsoid); whereas **Cartesian** means specified in distance from a specified origin, along specified X-Y-Z axes. A local 2D Cartesian reference system such as UTM uses only X and Y axes, and measurements from a specified point on the ellipsoid. One can be transformed mathematically to the other.

Geograhic ≡ geodetic and geocentric latitudes differ slightly. Geograhic/geodetic ϕ = angle between the equatorial plane and a line perpendicular to the ellipsoid at that point (generally used by default). Geocentric θ = angle between the equatorial plane and a line to the centre of the ellipsoid from that point (apps should specify if this is used).

From https://epsg.io/ (some are also found at https://spatialreference.org/):

EPSG:	ESRI WKT (or OGC WKT if no ESRI)
6283	DATUM["**D_GDA_1994**",SPHEROID["GRS_1980",6378137.0,298.257222101]]
4939	GEOGCS["**GDA_1994_3D**",DATUM["D_GDA_1994",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433],LINUNIT["Meter",1.0]]
4283	GEOGCS["**GCS_GDA_1994**",DATUM["D_GDA_1994",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]]
28356	PROJCS["**GDA_1994_MGA_Zone_56**",GEOGCS["GCS_GDA_1994",DATUM["D_GDA_1994",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]],PROJECTION["Transverse_Mercator"],PARAMETER["False_Easting",500000.0],PARAMETER["False_Northing",10000000.0],PARAMETER["Central_Meridian",153.0],PARAMETER["Scale_Factor",0.9996],PARAMETER["Latitude_Of_Origin",0.0],UNIT["Meter",1.0]]
1168	DATUM["**GDA2020**",SPHEROID["GRS_1980",6378137.0,298.257222101]]
7843	GEOGCS["**GDA2020_3D**",DATUM["GDA2020",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433],LINUNIT["Meter",1.0]]
7844	GEOGCS["**GCS_GDA2020**",DATUM["GDA2020",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]]
7842	GEOCCS["**GDA2020**",DATUM["Geocentric_Datum_of_Australia_2020",SPHEROID["GRS 1980",6378137,298.257222101,*AUTHORITY["EPSG","7019"]*],*AUTHORITY["EPSG","1168"]*],PRIMEM["Greenwich",0,*AUTHORITY["EPSG","8901"]*],UNIT["**metre**",1,*AUTHORITY["EPSG","9001"]*],AXIS["Geocentric X",OTHER],AXIS["Geocentric Y",OTHER],AXIS["Geocentric Z",NORTH],*AUTHORITY["EPSG","7842"]*]
7845	PROJCS["**GDA2020_GA_LCC**",GEOGCS["GCS_GDA2020",DATUM["GDA2020",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]],PROJECTION["Lambert_Conformal_Conic"],PARAMETER["False_Easting",0.0],PARAMETER["False_Northing",0.0],PARAMETER["Central_Meridian",134.0],PARAMETER["Standard_Parallel_1",-18.0],PARAMETER["Standard_Parallel_2",-36.0],PARAMETER["Latitude_Of_Origin",0.0],UNIT["Meter",1.0]]
7856	PROJCS["**GDA2020_MGA_Zone_56**",GEOGCS["GCS_GDA2020",DATUM["GDA2020",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]],PROJECTION["Transverse_Mercator"],PARAMETER["False_Easting",500000.0],PARAMETER["False_Northing",10000000.0],PARAMETER["Central_Meridian",153.0],PARAMETER["Scale_Factor",0.9996],PARAMETER["Latitude_Of_Origin",0.0],UNIT["Meter",1.0]]
4327	GEOGCS["**GCS_WGS_84_geographic_3D**",DATUM["D_WGS_1984",SPHEROID["WGS_1984",6378137.0,298.257223563]],PRIMEM["Greenwich",0.0],UNIT["degree minute second hemisphere",0.0174532925199433],LINUNIT["Meter",1.0]]
4326	GEOGCS["**GCS_WGS_1984**",DATUM["D_WGS_1984",SPHEROID["WGS_1984",6378137.0,298.257223563]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]]
3857	PROJCS["**WGS_1984_Web_Mercator_Auxiliary_Sphere**",GEOGCS["GCS_WGS_1984",DATUM["D_WGS_1984",SPHEROID["WGS_1984",6378137.0,298.257223563]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]],PROJECTION["Mercator_Auxiliary_Sphere"],PARAMETER["False_Easting",0.0],PARAMETER["False_Northing",0.0],PARAMETER["Central_Meridian",0.0],PARAMETER["Standard_Parallel_1",0.0],PARAMETER["Auxiliary_Sphere_Type",0.0],UNIT["Meter",1.0]]
9000	GEOGCS["**ITRF2014**",DATUM["International_Terrestrial_Reference_Frame_2014",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]]
9990	GEOGCS["**GCS_ITRF2020**",DATUM["International_Terrestrial_Reference_Frame_2020",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]]
7019	SPHEROID["**GRS_1980**",6378137.0,298.257222101]
5111	VDATUM["**Australian_Height_Datum**"]
5711	VERTCS["**AHD**",VDATUM["Australian_Height_Datum"],PARAMETER["Vertical_Shift",0.0],PARAMETER["Direction",1.0],UNIT["Meter",1.0]]
1292	VDATUM["**Australian_Vertical_Working_Surface**"]
9458	VERTCS["**AVWS_height**",VDATUM["Australian_Vertical_Working_Surface"],PARAMETER["Vertical_Shift",0.0],PARAMETER["Direction",1.0],UNIT["Meter",1.0]]
9463	GEOGCS["**GCS_GDA2020**",DATUM["GDA2020",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]],VERTCS["**AHD**",VDATUM["Australian_Height_Datum"],PARAMETER["Vertical_Shift",0.0],PARAMETER["Direction",1.0],UNIT["Meter",1.0]]

There are several "dialects" of Well Known Text (WKT) from ESRI (ArcGis) and OGC (PROJ, GDAL & QGIS). All comply with ISO 19111: 2019-23 because many attributes are optional. Maps from ESRI include all necessary information in ESRI WKT for correct projection and geo-referencing. Some EPSG codes are given as "Authority" in OGC WKT or "ID" in WKT2. OGC currently adds "ID" determined by PROJ, from ESRI WKT, to yield WKT2 aimed at easier information for humans. But PROJ sometimes makes errors, which can confuse apps that rely on it (even if they should according to OGC 2023 ignore "ID" in the event of conflict or confusion).

All dialects are clearer for humans to read with strategic line breaks.

The image shows EPSG:7856 in WKT2. This is similar to reports from gdalinfo, though they lack colour or indents. Great care is needed with [ ] structure in these reports to find what any ID refers back to.

See also: *Geospatial PDF Files.* https://scithings.id.au/geopdf.pdf

```
PROJCRS["GDA2020 / MGA zone 56",
    BASEGEOGCRS["GDA2020",
        DATUM["Geocentric Datum of Australia 2020",
            ELLIPSOID["GRS 1980",6378137,298.257222101,
                LENGTHUNIT["metre",1]]],
        PRIMEM["Greenwich",0,
            ANGLEUNIT["degree",0.0174532925199433]],
        ID["EPSG",7844]],
    CONVERSION["Map Grid of Australia zone 56",
        METHOD["Transverse Mercator",
            ID["EPSG",9807]],
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            ANGLEUNIT["degree",0.0174532925199433],
            ID["EPSG",8801]],
        PARAMETER["Longitude of natural origin",153,
            ANGLEUNIT["degree",0.0174532925199433],
            ID["EPSG",8802]],
        PARAMETER["Scale factor at natural origin",0.9996,
            SCALEUNIT["unity",1],
            ID["EPSG",8805]],
        PARAMETER["False easting",500000,
            LENGTHUNIT["metre",1],
            ID["EPSG",8806]],
        PARAMETER["False northing",10000000,
            LENGTHUNIT["metre",1],
            ID["EPSG",8807]]],
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        AXIS["(E)",east,
            ORDER[1],
            LENGTHUNIT["metre",1]],
        AXIS["(N)",north,
            ORDER[2],
            LENGTHUNIT["metre",1]],
    USAGE[
        SCOPE["Engineering survey, topographic mapping."],
        AREA["Australia - onshore and offshore between 150°E and 156°E."],
        BBOX[-58.96,150,-13.87,156]],
    ID["EPSG",7856]]
```