



Height Reference Systems

Reference Frames in Practice

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South African Geodesy Working Group Workshop| 1-2 October 2026



● Importance of height

- Which way does water flow?
- What is at risk during a flood?
- How should a city design its sewer network?
- How can irrigation deliver water efficiently?
- What gradients should roads and railways follow?
- What under-keel clearance does a ship need?
- How do we monitor sea-level change?
- What is the elevation of a mountain summit?



Photo:

<https://www.welt.de/vermisches/weltgeschehen/gallery9348988/Das-Jahrzehnt-der-Wetterkatastrophen.html>

But water flows, flood risk, drainage gradients and vertical datum comparisons require a physical height linked to gravity.

height anomaly links GNSS height to normal height



Talk roadmap

1

From Earth system to reference frames

Why reference systems, frames, surfaces and epochs matter.

2

Height systems and reference surfaces

Ellipsoid, geoid, quasigeoid, orthometric and normal heights.

3

From tide gauges to IHRS

MSL datums, geopotential numbers and global vertical unification.

4

South African and African implications

LLD, SAGEOID, TrigNet, data gaps and transition pathways.

5

Operational workflow

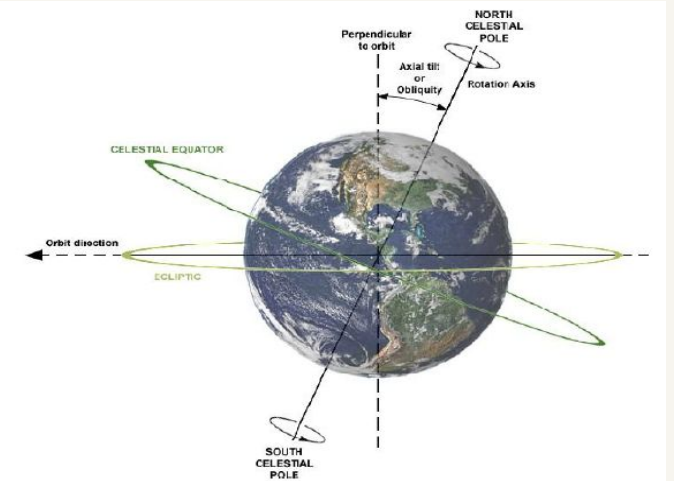
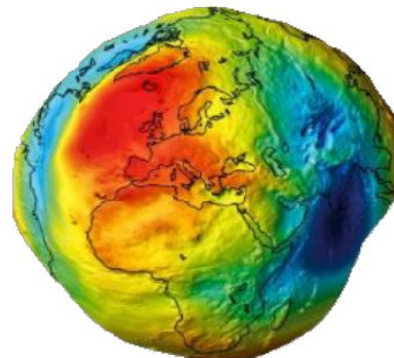
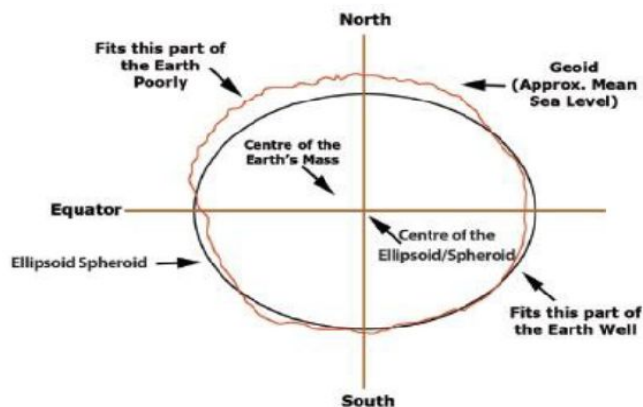
How practitioners move from GNSS coordinates to usable heights.

● Geodesy frames a changing Earth

Geodesy measures Earth's shape, gravity field and rotation as functions of space and time.

For heights, the critical extra ingredient is the gravity field.

Reference frames are therefore not merely map projections; they are infrastructure for a moving, deforming planet.



● Reference systems and reference frames

Reference system

The conventions, constants and models used to define coordinates.



Reference frame

The materialised realisation: stations, observations, coordinates, velocities and epochs.

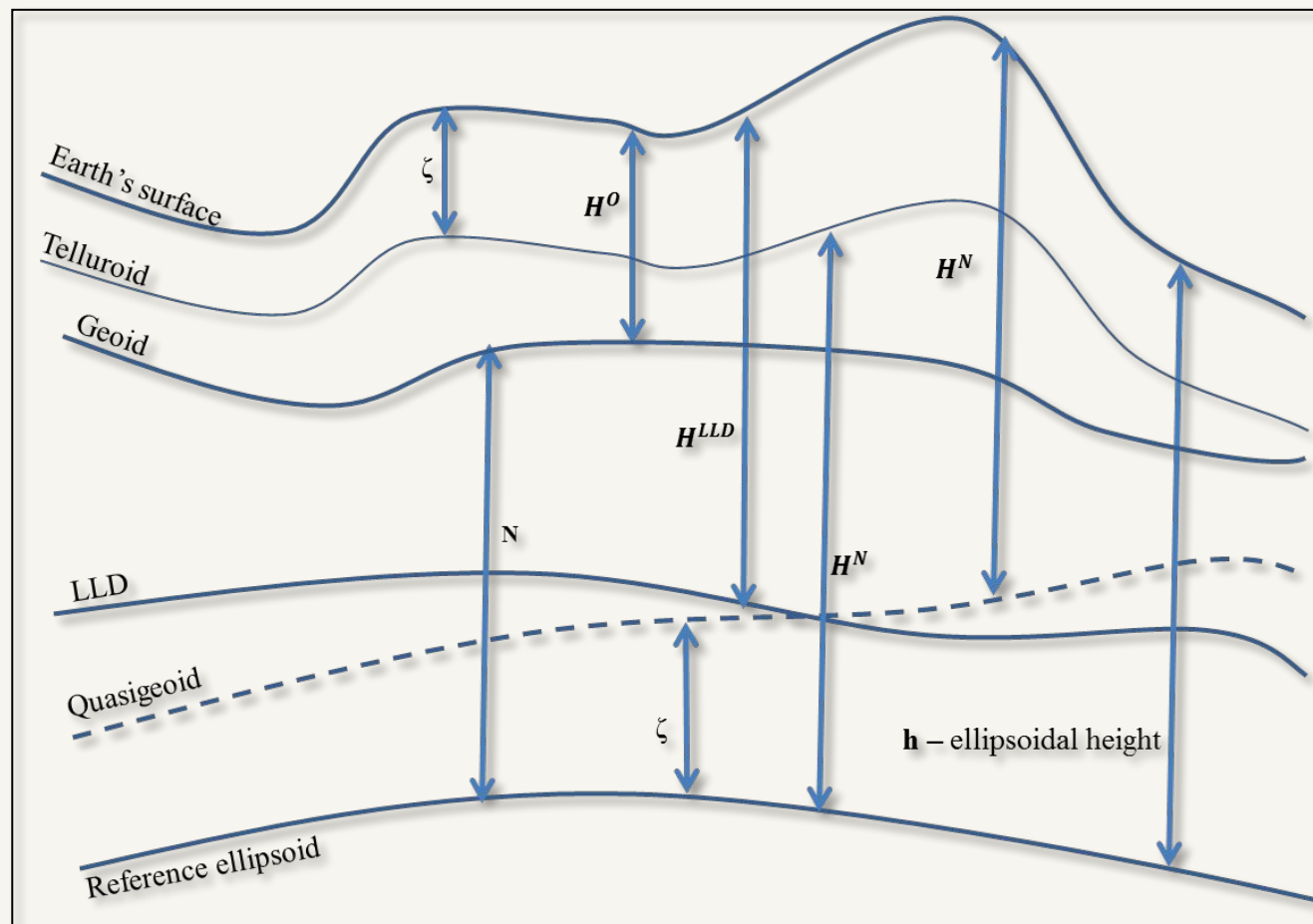


Operational datum

The form used by surveyors, GIS systems and infrastructure projects.

Vertical reference systems add a zero-potential surface and a convention for physical heights.

● Three surfaces to distinguish



Relationship between height reference surfaces and height systems.

Ellipsoid: mathematical surface used by GNSS.

Geoid: equipotential surface approximating mean sea level.

Quasigeoid: reference surface for normal heights.

● Height systems: what is being measured?

Ellipsoidal h	Geometric	Ellipsoid	GNSS-native; no gravity meaning
Orthometric H^O	Physical	Geoid	Distance along plumbline; requires mean gravity
Normal H^N	Physical	Quasigeoid	Uses normal gravity; widely practical
Spheroidal orthometric H^s	Approx. physical	LLD practice	South African legacy system; closer to normal
Dynamic H^D	Physical	Equipotentia l	Useful for hydraulics; limited geometry

● Physical heights start from geopotential

$$C(P) = W_0 - W(P)$$

geopotential number

$$H^o = C / \bar{g}$$

orthometric height

$$H^N = C / \bar{\gamma}$$

normal height

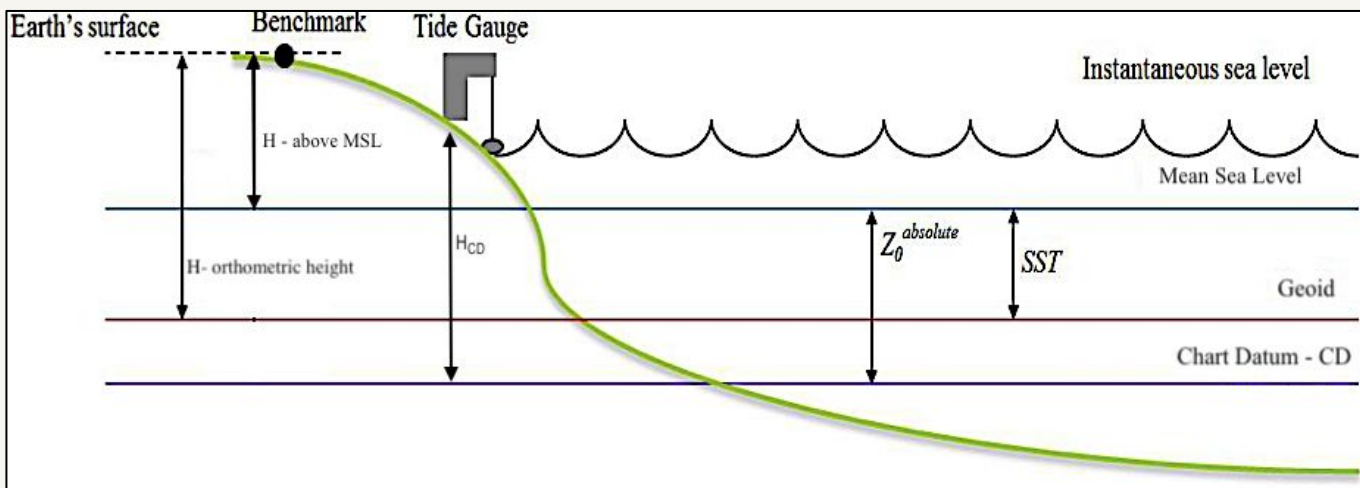
The geopotential number is the physically rigorous vertical coordinate. Heights are scaled forms of potential difference using actual mean gravity or normal mean gravity.

Key

consequence

Two locations with the same geometric height may not have the same physical height because gravity varies spatially.

● Why mean sea level is not enough



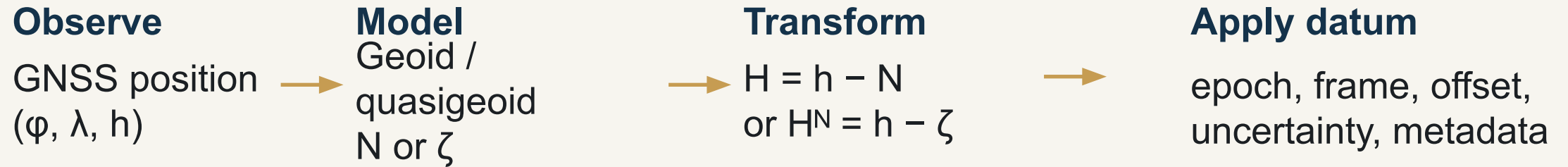
Relationship between Tide gauge and the MSL.

Traditional vertical datums use tide-gauge mean sea level as a zero, then transfer height inland by precise levelling.

But MSL is local: currents, winds, salinity, temperature, sea-surface topography and land motion all affect the observed “zero”.

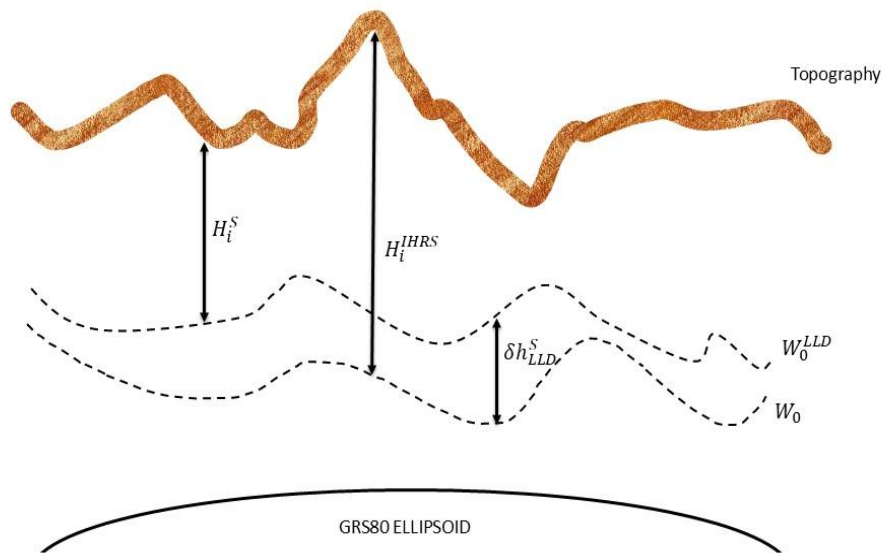
A local sea-level datum is useful, but it is not automatically a globally consistent equipotential surface.

● Modern heighting workflow: GNSS, gravity and geoid models



**The workflow is only as reliable as the weakest component:
GNSS frame/epoch, gravity data, geoid model, levelling ties,
transformation parameters and metadata.**

● IHRS: a global physical height system



The International Height Reference System (IHRS) defines physical heights through geopotential numbers referred to a conventional global potential value $W_0 = 62\,636\,853.4\,m^2s^{-2}$ (Burša *et al.*, 2001, 2004; Sánchez and Sideris, 2017).

The International Height Reference Frame (IHRF) is the realised network and coordinate set that makes the system operational.

Why it matters: local height datums become comparable across borders, continents and time.

● How IHRS connects to ITRF and space geodesy

ITRF realises the geometric frame using GNSS, VLBI, SLR and DORIS. IHRS/IHRF complements it with the physical vertical coordinate.

A modern national height datum should be traceable to both: geometric coordinates in an ITRF-consistent frame and physical heights in an IHRS-consistent system.

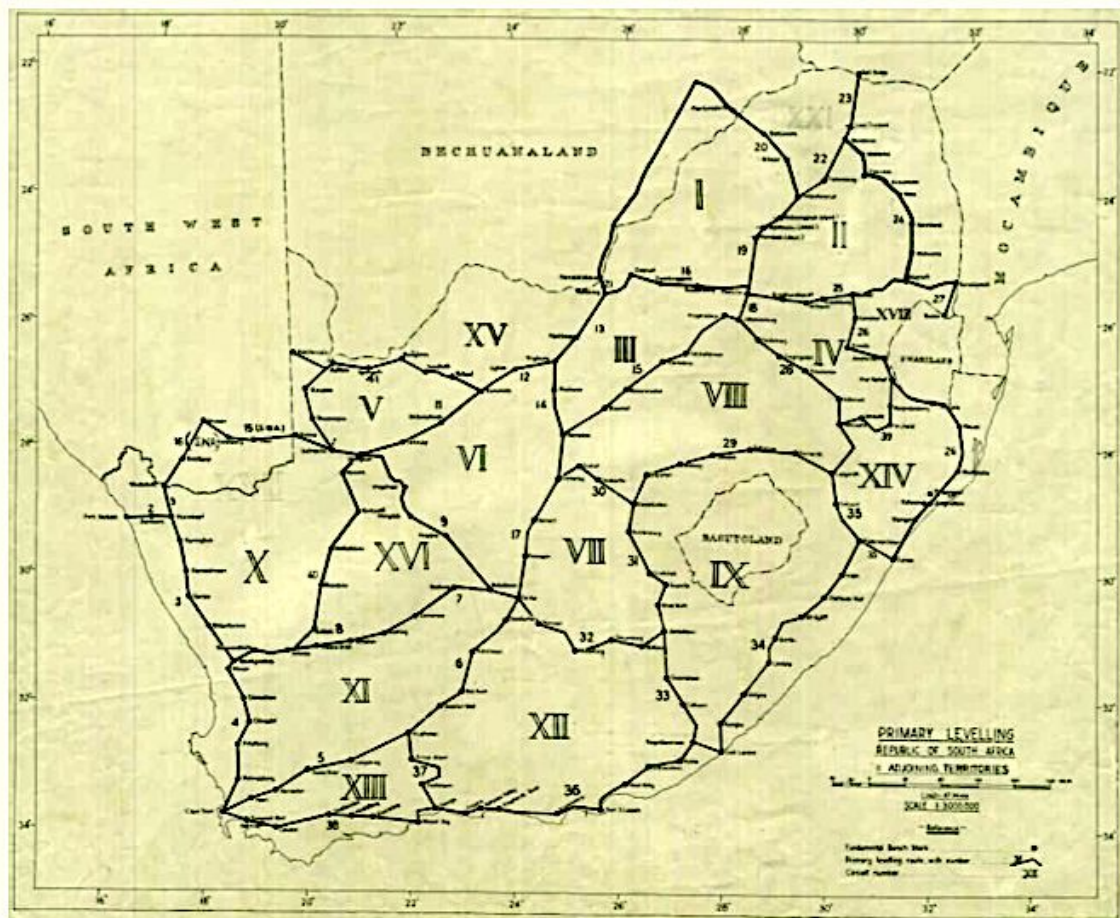
ITRF: geometry + velocity + epoch

co-located stations
GNSS/levelling
gravity observations
geoid/quasigeoid models



IHRS/IHRF: physical height + potential

South Africa's current vertical datum



South African first order levelling network (Wonnacott & Merry, 2012)

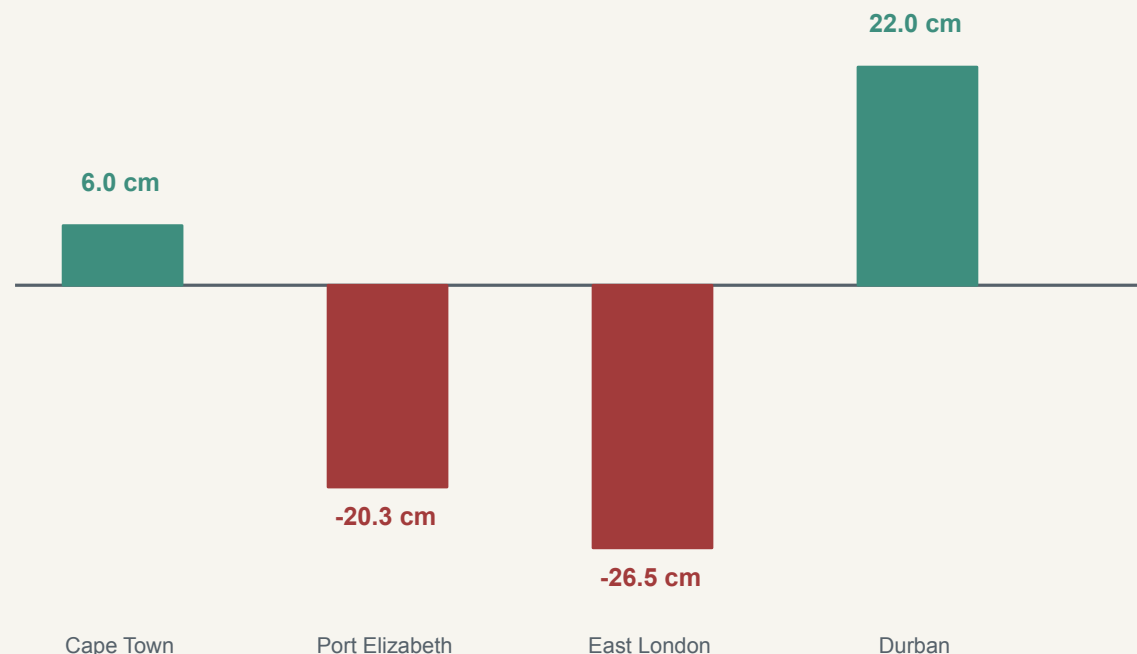
Land Levelling Datum (LLD)

- Set from mean sea level recorded at four tide gauges in the early 1900s.
- Precise levelling extended the datum inland.
- Classified as spheroidal orthometric height practice.
- Legacy system has distortions and is difficult to reconcile directly with GNSS-era positioning.

Modernisation should preserve LLD continuity and provide a documented link to IHRG

● What the South African research shows

Estimated LLD → global vertical datum offsets at four tide-gauge benchmarks



Research finding

The LLD shows stronger compatibility with a quasigeoid/normal-height approach than with a true geoid/orthometric approach.

This supports adopting a normal height system with a high-quality quasigeoid as the practical route for a geoid-consistent South African vertical datum.

● South African geodetic infrastructure

Terrestrial legacy

- LLD realised through fundamental benchmarks, benchmarks and precisely levelled TSMs.
- Horizontal control from trigonometrical network and TSMs.
- Legacy beacons are diminishing but remain important for datum traceability.

Modern space-geodetic layer

- TrigNet GNSS CORS network.
- IGS/GNSS stations and space-geodetic techniques: VLBI, SLR, DORIS.
- Future opportunities include expansion of geodetic VLBI and better co-location.

The transition is not from “old” to “new”; it is from separate legacy systems to an integrated reference-frame infrastructure.

● Why Africa needs a common vertical language

Common challenges

- Multiple national vertical datums
- Uneven gravity coverage
- Sparse or uneven GNSS/levelling ties
- Cross-border inconsistencies
- Limited metadata and transformation documentation

Applications that need consistency

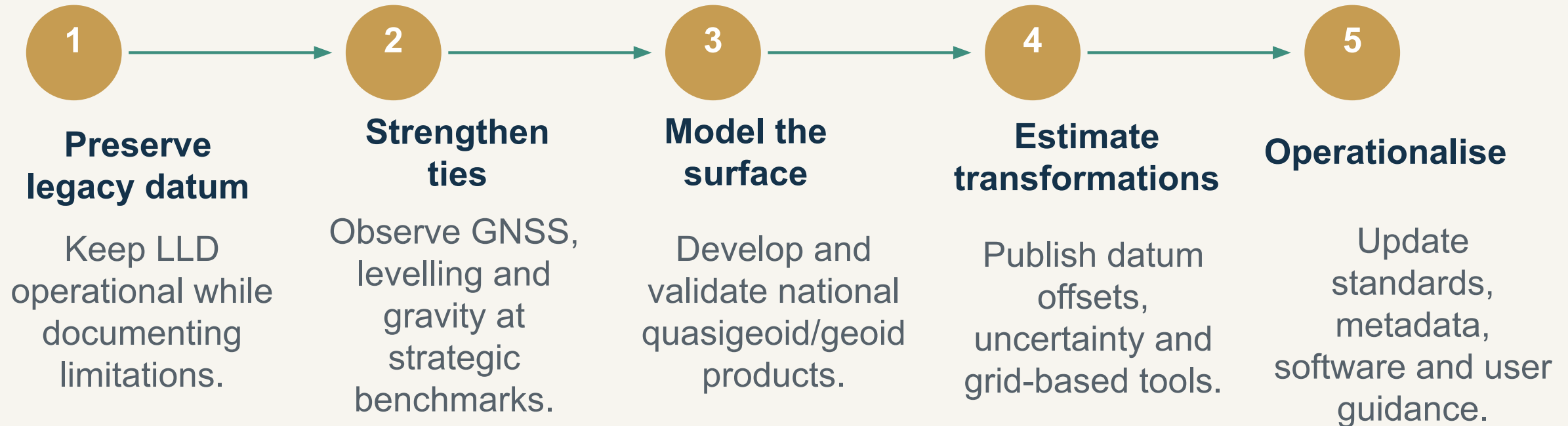
- River-basin and flood modelling
- Roads, rail, pipelines and coastal works
- Sea-level and land-motion monitoring
- Regional geoid modelling and AFREF integration
- Disaster-risk reduction and SDG reporting

IHRG/IHRF provides the common vertical language; national agencies provide the operational implementation.

● Data requirements for a robust geoid or quasigeoid

GNSS/levelling ties	Frame-consistent ellipsoidal heights and legacy physical heights
Gravity data	Terrestrial, airborne, marine and satellite gravity
DEM/topography	Terrain corrections and mass modelling
Tide gauges & land motion	MSL history, vertical land motion and coastal reference
GGM + regional modelling	Long wavelength field plus regional refinements
Metadata & uncertainty	Epoch, frame, tide system, model version, quality

● Transition strategy: preserve, connect and modernise



A pragmatic transition recognises that users need continuity, traceability and conversion tools — not only a theoretical datum definition.

Decision questions for practitioners

Before using a height, ask five questions:

- 1 What height type is it: h , H^O , H^N , H^s or H^D ?
- 2 What vertical datum/reference surface is it tied to?
- 3 Which horizontal frame and epoch produced the GNSS height?
- 4 Which geoid/quasigeoid model and transformation were used?
- 5 What is the uncertainty and metadata trail?

● Key messages

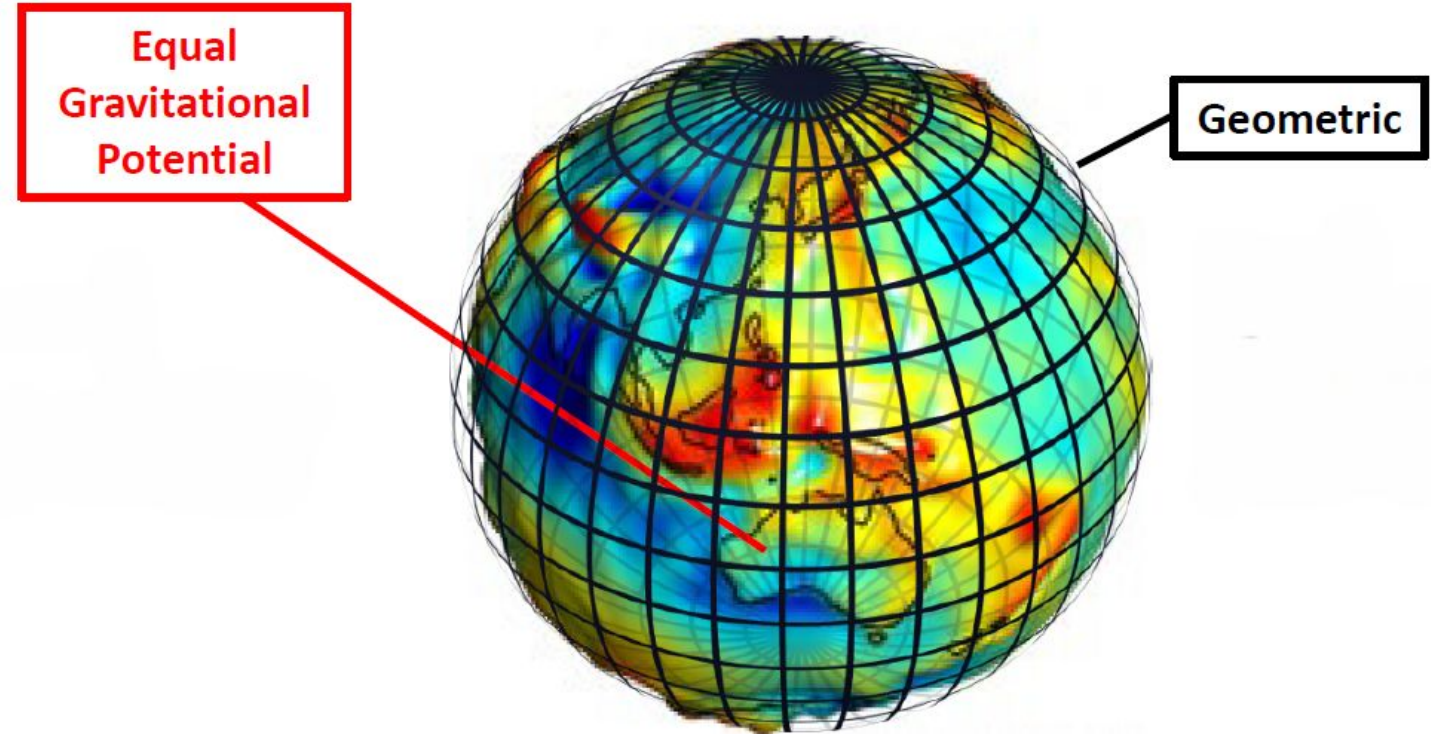


- 1. Height is physical, not only geometric.**
- 2. The geoid/quasigeoid is the bridge between GNSS and meaningful heights.**
- 3. Local MSL datums are historically useful but not globally uniform.**
- 4. IHRF/IHRF provides the global physical reference for vertical datum unification.**
- 5. South Africa's evidence supports a quasigeoid/normal-height transition path aligned to IHRF.**

Questions and discussion

Thank you

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Height connects geometry to gravity.