Time-Variable Gravity Signals and Their Uncertainties: An Assessment of the Current State of Knowledge

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1. Background

Technology for gravimetry and positioning are evolving, with major changes projected within the decade. These new technologies are anticipated to improve measurement accuracies such that: dynamic relative gravimeters would be accurate to < 1 milliGal; static relative gravimeters would be accurate to < 1 microGal; and static absolute gravimeters would be accurate to < 10 nanoGal. With instruments that are sensitive to signals several magnitudes smaller than currently possible, the question arises about which time-variable gravity effects (natural and man-made) will affect these more sensitive instruments. This study focuses on sources of gravity change that would be important to consider with a 1 nGal precision static instrument. Such precision would be available from a cold atom gravimeter, technology that is currently under development by several international research teams.

3. Conclusions

The gravity community has much work to do to fully-exploit a 1 nGal precision instrument.

Only one known source of gravity is well-constrained to the sub-nGal level (Earth Tides) and most sources have errors > 1 μGal. Error budgets on these gravity signals need to be reduced for use by a more precise instrument. The multi-disciplinary nature of the gravity sources will require diverse instrumentation; precise modeling; engineering; and continued collaborative work in monitoring the atmosphere, oceans, cryosphere, and earth surface change.

2. Summary of Findings

Regarding Source Magnitudes:

Largest Magnitude Gravity Source (Thousands of μGal /year):
- Instrument Drift

Smallest Magnitude Gravity Sources (Sub-μGal, alphabetical):
- Ambient Temperature
- Earth "Noise": Hum
- Earth "Noise": Microseisms
- Instrument Noise: Setup Error
- Sea Level Rise
- Subduction Zone Lithospheric Processes
- Variation in Length of Day

These gravity signals are best studied with a 1 nGal precision instrument

Gravity Sources of Unknown Magnitude:
- Coastal Erosion, which should be large based on the amount of mass moved but is not well-studied gravimetrically.
- Inner and Outer Core Free Wobbles, which are of agreed-upon small magnitude but are most well-studied for their frequencies.

Regarding Source Uncertainties:

Largest Uncertainty Gravity Sources (10,000s nGal /year, alphabetical):
- Instrument Drift (large variation by instrument)
- Landslides / Avalanches (natural variation, difficulty measuring),
- Coastal Erosion (not well-determined)

Smallest Uncertainty Gravity Sources (Sub- nGal):
- Earth Tides. These are so well-known that their timeseries are often used to calibrate superconducting gravimeters (the 3 largest tides).

Gravity Sources with Unknown Uncertainty:
- Near-Station Construction
- Continental Water Storage
- Near Sensor Mass Movement
- Present Day Ice Melting
- Ambient Temperature
- El Niño Southern Oscillation
- Variation in Length of Day
- Subduction Zone Lithospheric Processes
- Storm Surge, Wind Forcing, and Thermohaline Circulation
- Polar Motion
- Rain Events
- Water Vapor
- Soil Moisture / Snow
- Free Wobbles
- Earth "Noise": Hum Microseism

4. Catalog of Time-Variable Gravity (ġ) Signals

Decreasing Magnitude →

Mass Movements

Atmosphere

Local Pressure Loading
- **Max value: ~27 μGal**
- Within 50 km of station
- Rate: ~0.2 μGal/min
- Nominal: ~ 0.3 to 0.4 μGal / mbar
- Best accuracy when modeled at station
- Error: If hourly pressure measurements, accounting for topography, and reasonable weather, < 200 nGal. ~ 400 nGal in extreme weather. Refs: [1, 2, 3, 4, 29]

Regional Pressure Loading
- **Max value: 1-2 μGal**
- 50 - 1000 km from station
- Linear. ~ 0.078 μGal / mbar
- Error: If 1 barometer at station, 500 n Gal. If sparse network around station, <100 nGal. Topography errors are 400 nGal / km. Non-nominal air temperature structure yields up to 30 nGal.

Refs: [1, 2, 3, 4]

Global Pressure Loading
- **Max value: 1 μGal**
- >1000 km from station
- Complex correction, needs model.
- Error: Best modeling yields errors of several-hundred nGal near coasts and ~100 nGal inland. Extreme weather adds several-hundred extra nGal of error to this correction.

Refs: [1, 2, 3]

Ambient Temperature
- **Max value: Nearly 1 μGal**
- Often ignored
- Linear: 13 nGal / ˚C
- Error: Not well understood

Refs: [1, 3]

Water Vapor
- **Max value: Varies from 100 nGal (theoretically) to up to 1 μGal (measurements)**
- Often Ignored
- Local Effect
- Increases during rain events
- Error: Not well understood

Refs: [1, 2, 3]

Hydrology

Groundwater
- **Max value: 100-200 μGal**
- Rate: ~0.02 μGal/min
- Frequency: 1-8 cycles per day
- Highly variable both between groundwater systems and within a given system. Example: One system varied from -60 to 130 μGal, while another experienced ± 12-13 μGal cycles.

Refs: [1, 22, 26]

Rain Events
- **Max value: Tens of μGal**
- Rate: ~0.02 μGal/min
- Frequency: 1-8 cycles per day
- Error: Requires close collocation of rain gauges with gravity stations and modeling. Runoff causing widespread surface flooding is an effect not accounted for with rain gauges.
- Refs: [1, 2, 9]

Continental Water Storage
- **Max value: 3-10 μGal**
- Regional signal, well-resolved by satellite gravity time series (GRACE)
- Strong seasonal periods
- Example: Gravity varies by ± 3 μGal in the Mississippi River Basin as measured by GRACE

Refs: [2, 25]

Bodies of Surface Water
- **Max value: 1 to Tens of μGal**
- Within a few 100 km of station for small bodies (rivers, small lakes)
- Changes due to water mass and bed-load of sediments/rocks during storms.
- Error: Needs to be modeled, especially for rivers with a winding path. Very difficult to separate the water mass and bed-load effects. Refs: [9]

Soil Moisture / Snow
- **Max value: Several μGal**
- Rate: ~0.02 μGal/min
- Frequency: 1-8 cycles per day for soil moisture, Seasonal for snow
- Calculated globally (E.g. GLDAS/Noah Land Surface Model) or Regionally (E.g. North America NLDAS and The European Center for Medium-range Weather Forecasts (ECMWF)) Refs: [1, 25-27]

Erosion

Debris or Mud Flows
- **Max value: Several Hundred μGal**
- Rivers of rock, earth, or debris saturated with water
- Local effect, within minutes/hours
- Four instances in Taiwan, after a typhoon, yielded gravity changes between 27 ± 2 and 285 ± 3 μGal, depending on flow thickness and station proximity to the flow. Refs: [9, 14]

Landslides / Avalanches
- **Max value: Several Tens of μGal**
- Masses of rock, earth, snow, or debris moving downslope
- Local effect
- Occurs within minutes
- Two landslides in Taiwan, after a typhoon, yielded -41 ± 11 μGal and -32 ± 19 μGal gravity changes at two stations within a few 100 meters. Refs: [9, 14]

Coastal Erosion
- **Max value: Gravity value uncertain**
- Coastal erosion rates go as high as 80 m / yr in places in the U.S.
- Average erosion rates are 1-2 m / yr with extreme variability spatially and temporally.

Refs: [16, 17]

Volcanic or Earthquake

Large Eruptions
- **Max value: 400 μGal**
- Many events are of this size and can occur within a few hours
- Gravity may be recovered. One eruption example is that Mt. Etna recovered 100 μGal / hour to near-starting values.
- Error: Need gravimeters with 10 μGal to 100 nGal accuracies to measure eruption precursor activity. Refs: [2]

Inflation/Deflation
- **Max value: A Few Hundred μGal**
- One rate: 0.57 μGal / hour
- Can be regional, as with the Yellowstone volcanic area, or local
- Error: Need gravimeters with low, stable drift rates at the μGal or better level to measure this slow effect. Refs: [2]

Large Earthquakes: Coseismic
- **Max value: ± 20 μGal (GRACE estimates within a 200 km² area of Sumatra 2004 earthquake.)**
- SGs can't detect offsets from earthquakes of < 0.1 μGal.
- Gravimeters < 700 km from a medium to large earthquake may see offset.
- Gravimeter frequencies measured: 10 minutes to 24 hours. Refs: [2, 28]

Large Earthquakes: Postseismic
- **Relaxation max value: +12 to -4 μGal**
- **Permanent change: -13 to 12 μGal (Estimates from GRACE, Sumatra 2004 earthquake)**
- After earthquakes, deformation relaxation recovers some gravity. E.g. Sumatra rate: 1.5 μGal / month.
- Always after 26 months, gravity change is permanent. Refs: [1, 3]

Cryosphere

Present Day Ice Melting
- **Max value: A few μGal**
- Up to ± 3 μGal / yr, mountain glaciers.
- 80% of PDIM gravity created < 10 km from station. Remaining from < 50 km.
- Estimated with GPS+absolute gravity, or by modeling ice loss of nearby glaciers. Difficult to separate from GIA when both affect station, though possible. Refs: [13, 32, 33]

Glacial Isostatic Adjustment
- **Max value: A few μGal**
- GIA Nominally: -6.5 mm = 1 μGal.
- GRACE measures -1.33 μGal / year max of Fennoscandian and N. American GIA.
- Largest 10 mm / year uplift in Hudson Bay from GPS. Absolute gravity to the west agrees at 1.53 ± 0.38 μGal / yr.
- Best models agree with ground data to 1-2 mm / yr. Refs: [34-37]

Key:
AG = Absolute Gravimeter
SG= Superconducting Gravimeter

Non-Tidal Ocean Loading

Storm Surge, Wind Forcing, and Thermohaline Circulation
- **Max value: Ones to tens of μGal**
- E.g.: 2 m storm surge in southern North Sea = 6-8 μGal signals in coastal Europe and UK. 1 μGal., 600 km inland
- E.g.: In Finland, wind and current forcing cause 2-3 m of loading (as fast as 1 m / 12 hr. 1000 km inland, SG measures 3.1 μGal / m of loading. Refs: [2, 27, 29]

El Niño Southern Oscillation
- **Max value: 2-3 μGal at coastal equatorial stations**
- Multi-year period

Refs: [2]

Sea Level Rise
- **Max value: a few hundred nGal**
- SLR rate from 1993-2010: 3.2 mm/yr; Rate range projected for 2100: 5.1 to 8.6 mm/yr
- These roughly translate to gravity changes at coasts : from 1993-2010 of 133 nGal/yr, and 212 to 358 nGal/yr by 2100

Refs: [19]

Other

Oil and Gas Extraction / Mining
- **Max value: > 70 μGal**
- Varies by extraction technique, depth, mass removed, and location in area.
- One example: Secondary recovery of oil through water injection in Prudhoe Bay, AK changed gravity by 70 μGal in 4 years over a several hundred km² area. Similar rates reported in Norway of -3.75 to +15 μGal / year Refs: [2, 19]

Construction
- **Max value: No upper Limit**
- Depends on the mass moved and distance from the instrument
- One example: 3 μGal total effect of a new parking lot and new nearby building. Effect modeled by modifying a local DEM.

Refs: [13]

Nearby Small Mass Movement
- **Max value: Depends on mass and proximity to instrument**
- E.g. People or other machinery
- A 50 kg (110 lb.) person 0.5 m away is a 2 μGal signal.

Refs: [31]

Miscellaneous Processes
- **70 nGal for subduction zone processes** Refs: [18]
- **Vegetation biomass** (modeled in Land Use Models like GLDAS) changes by ± 5 kg/m² yearly and gravity effect is detectable in GRACE harmonic models' degrees 4-14. Ref: [23]

Tides, Earth Motion, Earth Noise

Earth Tides
- **Max value: 300 μGal**
- Periodic, Rate Max: 1 μGal / min
- Magnitude and rate vary with latitude and phase of lunisolar cycle
- Error: Varies with model type and number of tides used. Largest 3 tides: Diurnal, Semidiurnal, Annual. Two estimates of best accuracy: 0.1 nGal (2009) and 0.39 nGal (2013). Refs: [1, 2]

Ocean Tidal Loading- Global
- **Max value: < 33 μGal**
- Global effect often less, e.g. 5-10 μGal in Canada
- Periodic signal. Usually use 9 waves: 4 diurnal, 4 semidiurnal, and 1 monthly
- Can use TOPEX/POSEIDON data
- Error: One estimate is 5 μGal. Another study says biggest errors are in regional tidal loading. Refs: [1, 2, 5]

Ocean Tidal Loading- Regional
- **Max value: 50-100% of global (16.5 - 33 μGal)**
- Periodic; complex near the coastline and with coastal bathymetry
- Regional modeling is necessary
- Error: One estimate says with careful modeling, 0.05-0.1 μGal. Another says a regional model coupled to a global, 0.1 μGal (as of 1998). Refs: [1, 3, 5]

Earth's Motions
- **Polar motion max value: 15 μGal**
- Polar motion: Annual (365 days) and Chandler (435 days) periods
- **Length of day max value: < 500 nGal**
- LOD corrections frequently neglected
- **Nearly diurnal free wobble max value: Uncertain.**
- Period: ~430 days; -(1 + 1/434.1 ± 0.9) cycles per sidereal day. Refs: [2, 24]

Earth "Noise": Microseisms
- **Max value: < 1 μGal**
- Complex; seasonal and latitudinal
- Most are Rayleigh waves 0.04 - 1 Hz. Primary microseisms (0.05-0.08 Hz) created by breaking waves near shore. Secondary (larger magnitude than primary, 0.1-0.16 Hz) created by downward pressure waves. Deep ocean creates P-waves and core phases 0.1-1.4 Hz. Refs: [11]

Earth "Noise": Hum
- **Max value: < 1 μGal.**
- Just above the detectable limit for stacked SG signals from quiet sites.
- Periodic, seasonal influences
- 5- 20 mHz. E.g. Waves traveling south along Pacific coast of N. America excite a hum in the 2.5 -8 mHz range.

Refs: [12, 30]

Instrumentation

Instrument Noise
- **Tares max value: Varies by instrument. 5 μGal common for AG/SG**
- Tares caused by instrument malfunction, mechanical shock, electrical disturbance, etc.
- **Drift: Tens to hundreds of μGal/day. Varies by instrument.**
- **Setup error: < 1 μGal (tilt, etc.)**

Refs: [1, 20, 29]

Instrument Self-Attraction
- **Max value: -1.7 to 0.5 μGal (AGs)**
- Attraction between instrument pieces and test mass in instrument for precise gravimeters.
- Error: 0.1 - 0.2 μGal.
- Largest errors in calculation are setup error and simplifications to the instrument modeling.

Refs: [6, 7, 8]