EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS

VOLUME 80 NUMBER 11

MARCH 16, 1999

PAGES 121—132

Network of Superconducting Gravimeters Benefits a Number of Disciplines

PAGES 121, 125-126

A global network of superconducting gravimeters (SGs) is compiling significant data for a range of important studies spanning a number of disciplines concerned with the Earth's gravity, tides, environment, and geodetics. Among phenomena being looked at are seismic normal modes, the Slichter triplet, tidal gravity, ocean tidal loading, core nutations, and core modes. Hydrologists and volcanologists also may benefit from SG data.

The network was set up by the Global Geodynamics Project (GGP), an international program of observations of temporal variations in the Earth's gravity field. Observations began in 1997 and will continue until 2003. Eighteen SGs currently are in operation in the network (see Figures 1 and 2).

Those involved point to the flurry of papers in the last year on atmospheric excitation of the Earth's normal modes as just one example of the value of the SGs. The network is expected to contribute much useful data to the study of these modes and the energetic turbulence in the atmosphere that excites them. SGs are able to detect as well local gravity changes associated with slow and silent earthquakes.

SG data also is expected to contribute substantially to continuing efforts to detect and characterize Slichter triplet frequencies and to help resolve uncertainties in tidal gravity studies and discrepancies in ocean tidal loading models in coastal regions. The list goes on.

The SGs sample the gravity field every 1–10 s with a precision of <1 nGal. The estimated accuracy of the measurements, including calibration errors, is of the order of 0.1 μGal. Data at all sites are checked against less frequent measurements by absolute gravimeters. Observations began the summer of 1997. The 6-year duration was chosen to permit the 14-month Chandler wobble to be clearly separated from annual variations of gravity. The Chandler wobble is the orientation of the Earth's rotation with respect to its figure axis. Data from the GGP stations are being sent to the International Center for Earth Tides (ICET) in Brussels, which is making it available to the scientific community.

Need for Coordination

The need for coordination of accurate global gravity measurements was recognized in the early days of the Study of the Earth's Deep Interior (SEDI) in the mid-1980s. Already the tidal gravity community had begun to acquire SGs for various studies of tides and for environmental and geodetic purposes. It was realized that a coordinated global effort would result in the best site selection for SG stations, would encourage the stations to acquire data in a uniform manner, and would permit data to be stacked to search for global signals that could be separated from local or regional gravity effects.

In the past 15 years, the versatility of the SGs has been repeatedly demonstrated over a very wide frequency range. Their signal-to-noise ratio in the seismic normal modes band is remarkably good, falling only marginally short of the very best spring gravimeters and broadband seismometers. The ratio permits useful data to be added to the global seismic network (GSN). At periods longer than 1 hour, the SGs' stability exceeds that of the best seismometers, and they have performed very well in tidal studies and in all periods up to several years.

SGs are not entirely drift free, however, despite improvements. But several stations are now reporting drifts of only about 1μGal/yr, and the type of drift is a well-defined function of the instrument (generally linear or exponential). For long-term variations of the gravity field, the very best site would combine an SG with colocated measurements by an absolute gravimeter at regular intervals. The SG provides an invaluable time history of gravity at the site and the absolute gravimeter provides the absolute reference from which drift and secular changes can be inferred.

Seismic Normal Modes

The GSN includes several hundred broadband seismometers that are the basis for determining body wave travel times and normal mode eigenfrequencies. Recent comparisons of typical Sgs with the best spring gravimeters and the STS-1 seismometer have shown that the Sgs have slightly higher noise in the 200-600-s period range, but they can clearly record normal modes between periods of from about 10 s to 54 min. Even with only 18 currently recording Sgs, their high sample rate data (1-2 s) will be quite useful to the GSN network. Seismic normal modes and other SG gravity signals are displayed in Figure 3.

Papers on the atmospheric excitation of the Earth's normal modes have included data from the SG at Syowa (SY) in the Antarctic (see Figure 2). Some of the studies have demonstrated that the International Deployment of Accelerators network, which uses spring gravimeters, can clearly see the background spectrum of the normal modes, whose amplitudes are at the nGal level. Theoretical estimates seem to verify that the atmosphere has sufficiently energetic turbulence, generated by solar radiation, to excite these modes. The GGP network will be able to add much useful high quality data to study this phenomenon.

Also associated with normal modes, but generated by less well-defined processes, are the slow and silent earthquakes first identified more than a decade ago. SGs, because of their sensitivity and stability over long times, are certainly able to detect the direct gravity changes associated with such events. But a significant problem exists in separating such signals at a single station from gravity variations caused by the environment. The use of a local SG network over ranges of several 100s of km (such as some in Europe and Japan) would seem to offer the best configuration for such work.

The Slichter Triplet

Much effort has been expended over the past decade to detect and characterize the elusive trio of frequencies, known as the Slichter triplet, of the inner core translation. The frequencies are split into 3 components by the Earth's rotation. The signals are thought to lie within the short period tidal band (4-8 hours); for example, for the preliminary reference Earth model, assuming an inviscid core, the periods are approximately 4.77, 5.31, and 5.98 hours for the retrograde, central, and prograde motions, respectively.

These periods are critically dependent on the assumed density jump at the inner core-outer core boundary (ICB), and therein lies the interest in trying to detect the motion. Several reports have made positive claims for detection, but

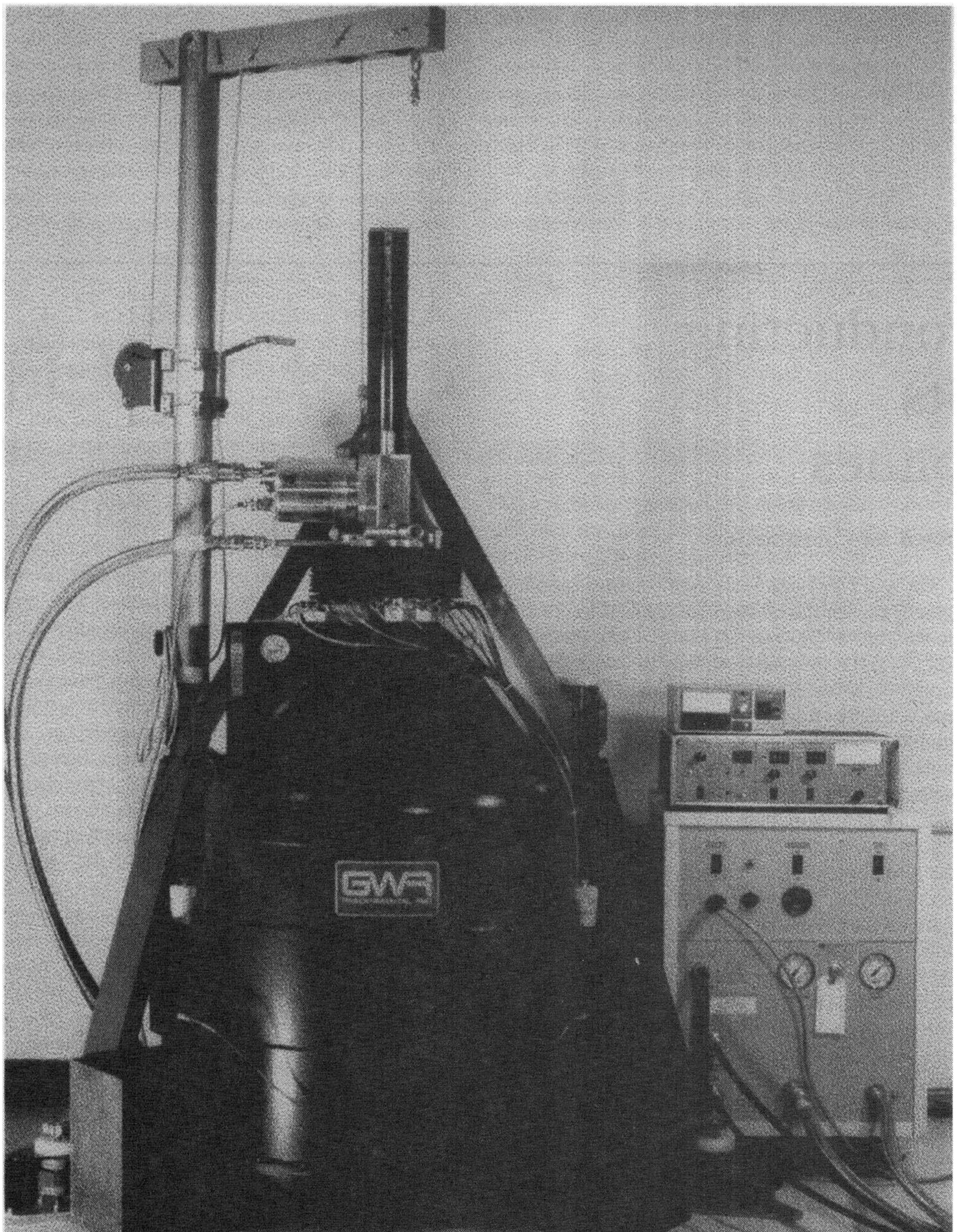


Fig. 1. One of the new generation of superconducting gravimeters. The sensor uses an Nb superconducting test mass that is levitated in a magnetic field created by superconducting coils. The extremely low noise and low drift are primarily due to the operation of the components at liquid He temperatures regulated to a few micro-Kelvin inside a vacuum can. The model shown is equipped with two vertically spaced sensors to measure gravity and gravity gradient. A special refrigeration unit allows the instrument to be run indefinitely with only one filling of liquid He. All aspects of the model can be monitored remotely by modem. Original color image appears at the back of this volume.

each time there have been objections on either observational or theoretical grounds. Debate continues about the excitation mechanism of this motion—by fluid motion in the outer core or perhaps by a sufficiently energetic earthquake—and uncertainty exists about its damping mechanism. Assuming favorable conditions, the GGP data will provide an ideal opportunity to finally observe this triplet and discover the answers.

Earth Tides and Ocean Tidal Loading

Theoretical models of the solid Earth tides are now so accurate that some consider this a solved problem in the dynamics of the solar system. Even the smallest contributions to the attracting forces, such as from subtle interactions between Venus and Jupiter, are included to a level of about an nGal in the latest tidal potentials. Tidal gravity, however, is modified by the elastic structure of the Earth's interior and by the dynamics of the oceans and the atmosphere, so the measured tides have much larger uncertainties. The tidal community has been concerned with whether lateral changes occur in the gravimetric phase and other problems. For such purposes gravimeters need to be precisely calibrated against an absolute reference to about 0.1%, an important consideration for GGP.

The response of the oceans is still a problem. The new generation of ocean tide loading models, which all include data from the TOPEX/POSEIDON satellites, agree quite well for most of the open oceans. However, significant discrepancies exist in most coastal regions, particularly in the southwestern Pacific and around Antarctica. The distribution of GGP stations is not ideal, and the closeness of most of the stations (<500 km) to the coast is both an advantage in that ocean loading is significant and a disadvantage in that tidal loading is the least well-known ingredient of tidal analysis. Already, however, SG data from Japan have been successfully used to model the steric effect, which is the change in mass of the oceans from thermal expansion, a factor that is additional to ocean tidal loading.

Core Nutations

The diurnal frequency band is of primary importance in investigating the resonance in the solid Earth tides originating from the free core nutation (FCN), which is associated with the wobble of the fluid core with respect to the mantle. This eigenperiod is observed to be just under a day in the mantle reference frame and approximately 435 days in the space reference frame. Fortunately some tidal waves are close to this eigenfrequency, which generates a resonance. The high quality of tidal measurements now available with SGs constrains the period and damping of the FCN as well as the gravimetric factor, which determines the strength of the resonance. Because of a direct link between tides and the forced nutations of the Earth in space, an identical resonance exists in the lunisolar nutations. This is well observed in very long baseline interferometry (VLBI). The diurnal resonance perturbs the tidally induced elastic response of the Earth not only in gravity but in all possible deformational aspects (radial and transverse displacement, tilt, strain). Very recently fre-

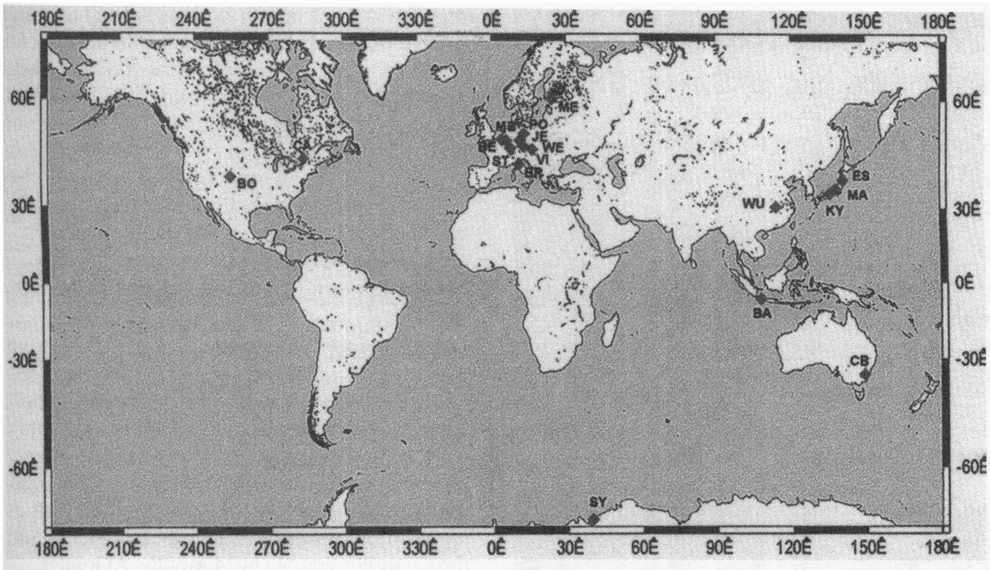


Fig 2. The Global Geodynamics Project network showing recording stations as of December 1998. Original color image appears at the back of this volume.

quency-dependent Love and Shida numbers retrieved from VLBI data have indicated an FCN resonance period of about 426 sidereal days. Apart from the resonant modification of the tides and associated nutations, another possibility would be to observe the eigenmode directly and to infer its eigenperiod and damping.

Analogous to FCN, the free inner core nutation (FICN) is another free mode predicted for the rotation of a (slightly tilted) solid inner core coupled to the outer core and mantle. This mode is nearly diurnal, like the FCN, but is in the prograde direction close to the prograde diurnal wave. It has a weaker resonance than the FCN, and the uncertainty related to the atmospheric forcing at the diurnal wave frequency makes gravimetric observations very difficult to interpret. Detection would lead to useful information on ICB flattening and ICB density jump, which are still controversial in seismological studies, as well as on elastic properties of the solid inner core.

Core Modes

Core modes, sometimes called core undertones or, more correctly, inertial-gravity waves, refer to the inherent property of a confined rotating fluid to oscillate; rotation and buoyancy are the restoring forces. These modes can in principal be detected either through subtle changes in rotation of the mantle, for modes with azimuthal number ±1, or through gravimetry in the tidal band. Their spectrum is still not completely mapped for all possible values of the buoyancy frequency of the fluid core. Enough is known, however, to suggest they have a dense, if not infinitely dense, spectrum. Therefore it is unlikely for individual modes to be clearly identified unless the excitation mechanism is highly selective.

Unexplained peaks in the gravity spectrum at periods between 12 and 24 hours have sometimes been attributed to such modes. But closer examination has always cast doubt on this because of poor signal-to-noise ratio or a lack of confirmation by other instruments. It will be interesting to combine all the GGP data in this period range to see if global features can be detected that are not evident in the individual noise spectra. Because these modes are probably only very weakly damped by viscous or magnetic forces, they could be quite persistent even though elliptical instabilities and mode mixing complicate the situation.

Atmosphere-Solid Earth Interactions

In atmospheric interactions with the solid Earth, pressure-induced gravity changes are seen as "noise" and have to be corrected for. At the same time well-identified gravity signatures can help in learning about atmospheric dynamics. In most gravity studies, local atmospheric pressure contributions are removed using a barometric admittance close to -0.3 μGal/mbar. This factor is a constant, but introduction of a frequency-dependent admittance (or a convolution filter in the time domain) is better able to account for local effects, even though this procedure is clearly inadequate to model regional or global atmospheric loads.

A global approach is needed for annual and diurnal pressure waves (and their harmonics), which are thermally driven by solar heating and are known to be of planetary extent. The classical correction obviously fails because the atmospheric loading strongly perturbs gravimetric amplitude and phase factors (this also affects determination of the FCN). Moreover, because of seasonal amplitude modulation, other waves are also perturbed and could possibly alter FCN retrieval from gravimetric data.

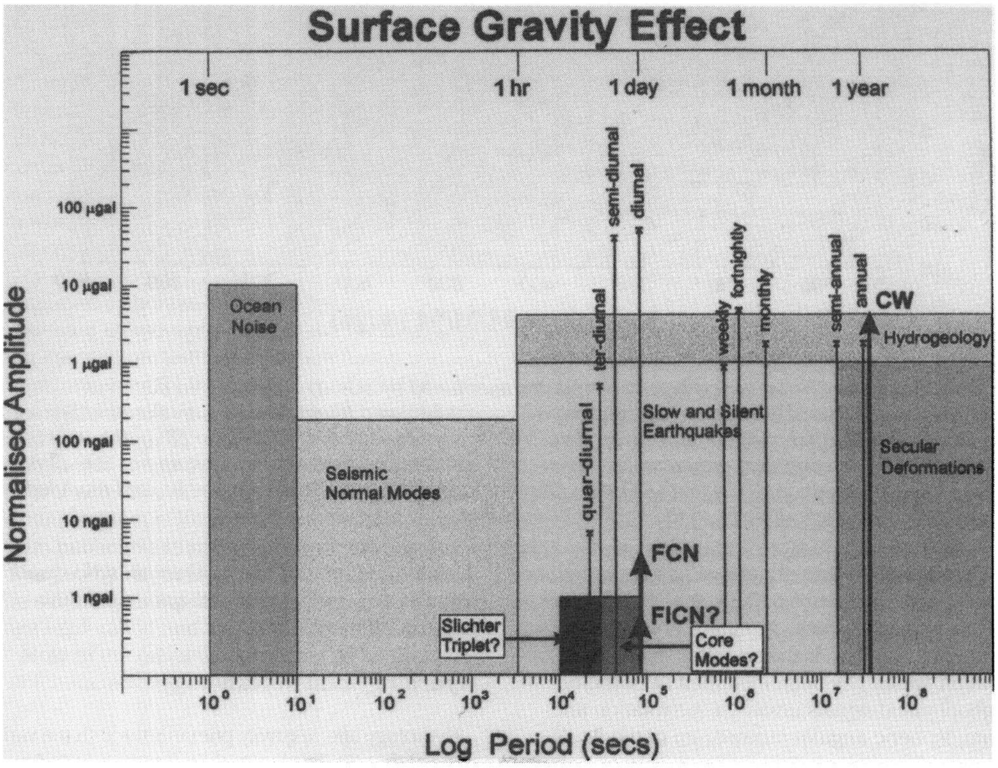


Fig. 3. Representation of the gravimetric effect of various signals at midlatitudes, using harmonic amplitude normalization. The atmospheric pressure effect is omitted because the amplitude of the background variability is dependent on the record length. Likewise, ocean tidal loading, also not shown, is highly station-dependent. Both of these signals have significant strength at tidal line frequencies. Original color image appears at the back of this volume.

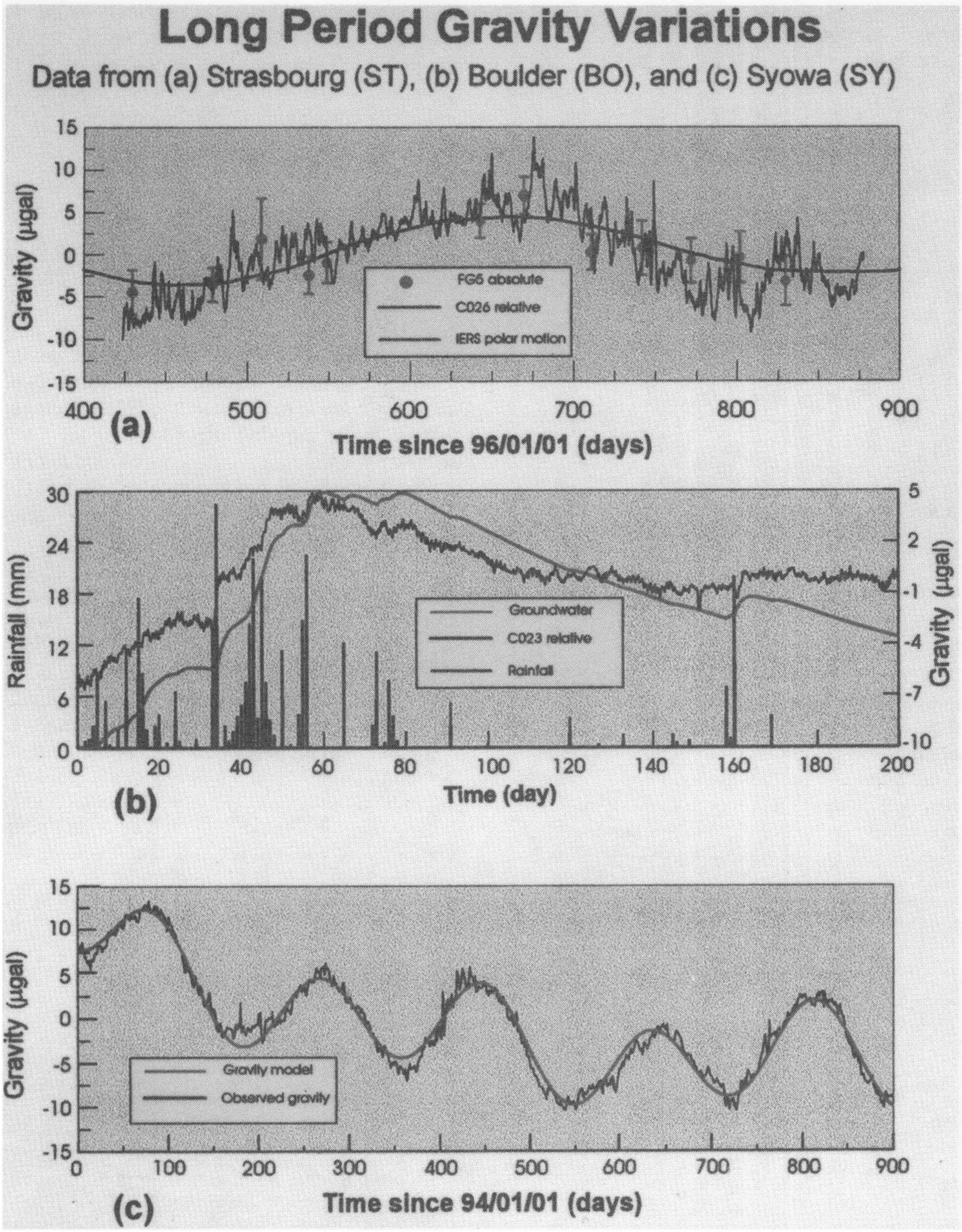


Fig. 4. Examples of long period gravity variations determined by SGs. a) Five hundred days from Strasbourg, France (ST; see Figure 2), showing agreement between International Earth Rotation Service polar motion, SG, and absolute gravimeter data; b) 200 days from Boulder, Colorado (BO), showing how rainfall and computed groundwater can account for significant gravity changes; and c) 900 days from the Syowa station, Antarctica (SY), showing that long-term gravity changes can be well modeled. Original color image appears at the back of this volume.

In addition to these tidal signals are other atmospheric processes of large spatial extension with a specific gravity signature. A very interesting phenomenon is the so-called 40-50 day oscillation, which has been identified in numerous geophysical signals involving the rotation and atmospheric angular momentum of the Earth-atmosphere system. A coupling mechanism between the atmosphere and the solid mantle is caused by the large-scale pressure field and associated velocity field. It is therefore reasonable to expect a loading contribution in gravity from this pressure field, and there is some evidence of such a signal in individual SG records. No doubt a stack of SG records will enhance our knowledge in all these directions.

Hydrology and Volcanology

Hydrology affects gravity primarily through the variation of the water table, which in turn is modified by effects such as regional rainfall or severe local storms. It is therefore not surprising to find that SG data contain many examples of a correlation between rainfall, groundwater, and gravity (see, for example, Figure 4b). In most cases, simple models of one or two aquifers with exponential recharge and discharge timescales are sufficient to account for variations of groundwater of several nGal over weeks or even shorter. Clearly such signals are not global but depend on local or regional conditions; nevertheless, they must be taken into account before global long period signals can reliably be identified.

Another interesting application of high precision gravimetry is in the monitoring of major volcanic areas. However, the cost of a small network of SGs has so far prevented a major campaign in this area.

Long Period Response

Gravimetry is practically the only tool, besides Earth rotation measurements such as VLBI, for investigating the response of the Earth to intermediate period forcing (hours to years). Beyond the diurnal signals are long period tides (fortnightly, monthly, semiannually, and annually) and the Chandler wobble at 14 months. At longer periods, the next important forcing, unfortunately at too long a period for GGP, is the 18.6-year Bradley wave, which has still to be observed.

The long period tides of less than a year are well defined by analysis of SG records that extend for some sites back almost a decade, yielding gravimetric delta factors that are generally in agreement with elastic theory. The situation at the annual and Chandler periods is less clear because of a lack of adequate long records of sufficient quality. ICET has analyzed 12 years of data to separate these periods. Analysis of 8 years of data shows the recovery of the annual gravimetric delta factor with an amplitude close to 1.2, though with a positive phase, which, if verified by more extensive data, would suggest a response that is not entirely elastic. GGP will permit the annual and Chandler gravimetric factors to be much more precisely determined in future.

Figure 4a shows an example of the retrieval of the polar motion using data from both an SG and an absolute gravimeter carried out over a year and a half in Strasbourg (ST). The SG data has had a linear drift of a few µGal/yr removed, but otherwise the same local solid Earth and ocean tide has been subtracted from both data sets. The two gravity data sets are in excellent agreement, and their joint agreement with the IERS polar motion data set confirms the long-term gravity variations at this site. Many similar analyses have been done by GGP groups.

Those interested in GGP may visit its home page (http://www.eas.slu.edu/GGP/ggphome.html), which contains a list of publications and details of the GGP stations.

Authors

D. Crossley, J. Hinderer, G. Casula, O. Francis, H.-T. Hsu, Y. Imanishi, G. Jentzsch, J. Kääriänen, J. Merriam, B. Meurers, J. Neumeyer, B. Richter, K. Shibuya, T. Sato, and T. van Dam
For more information, contact D. Crossley, Department of Earth and Atmospheric Sciences, St. Louis University, 3507 Laclede Ave., St. Louis, MO 63103 USA; E-mail: crossley@eas.slu.edu

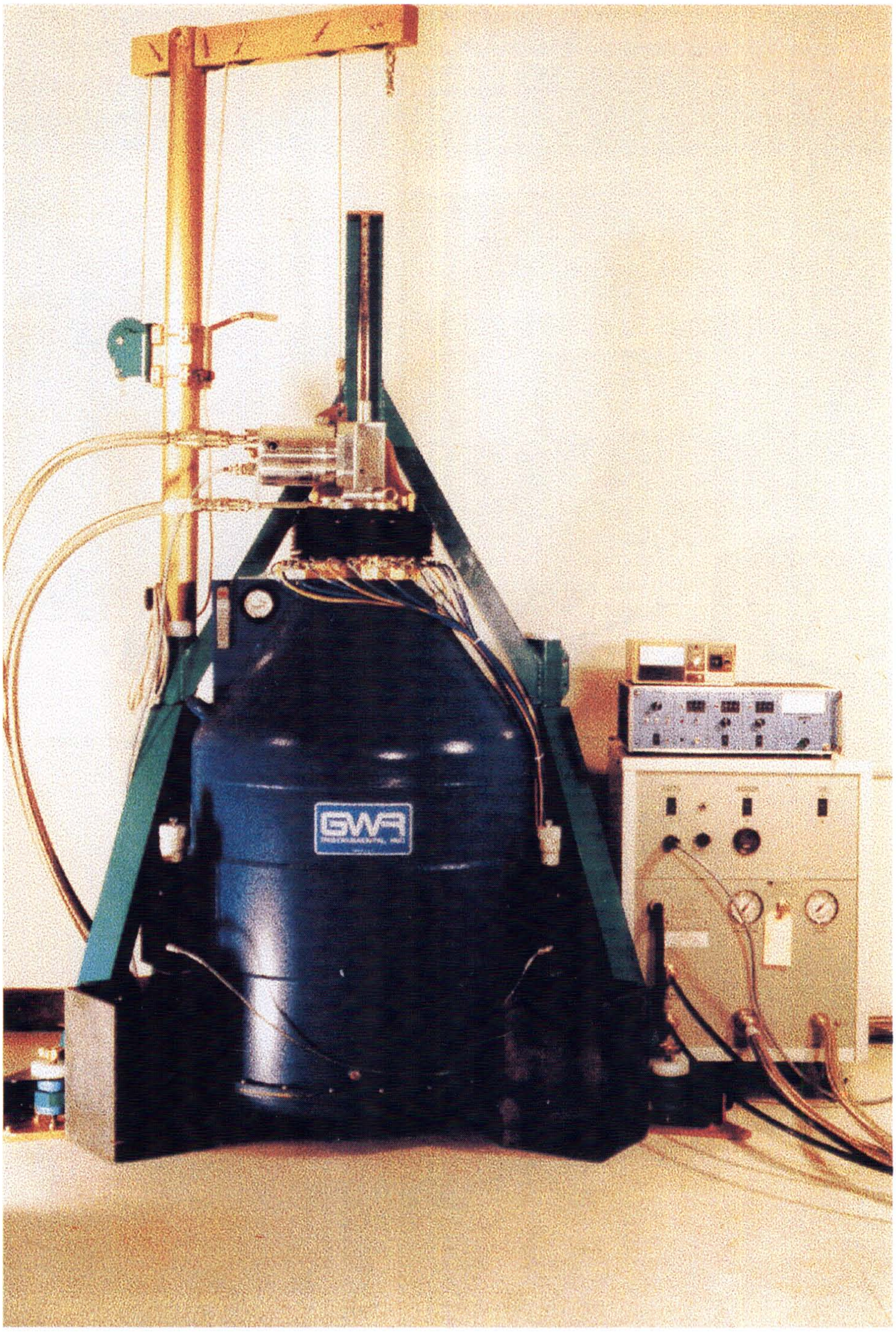


Fig. 1. One of the new generation of superconducting gravimeters. The sensor uses an Nb superconducting test mass which is levitated in a magnetic field created by superconducting coils. The extremely low noise and low drift are primarily due to the operation of the components at liquid He temperatures regulated to a few micro-Kelvin inside a vacuum can. The model shown is equipped with two vertically spaced sensors to measure gravity and gravity gradient. A special refrigeration unit allows the instrument to be run indefinitely with only one filling of liquid He. All aspects of the model can be monitored remotely by modem.

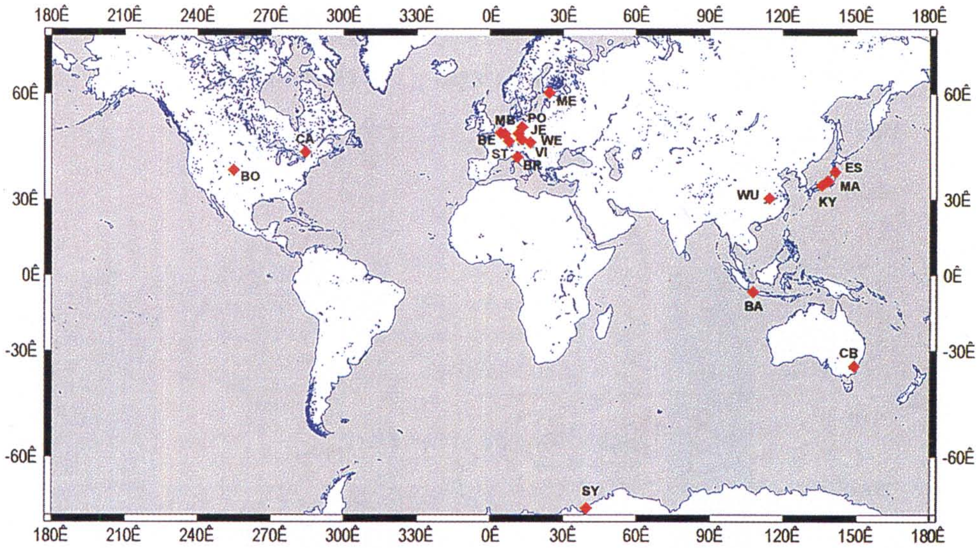


Fig 2. The Global Geodynamics Project network showing recording stations as of December 1998.

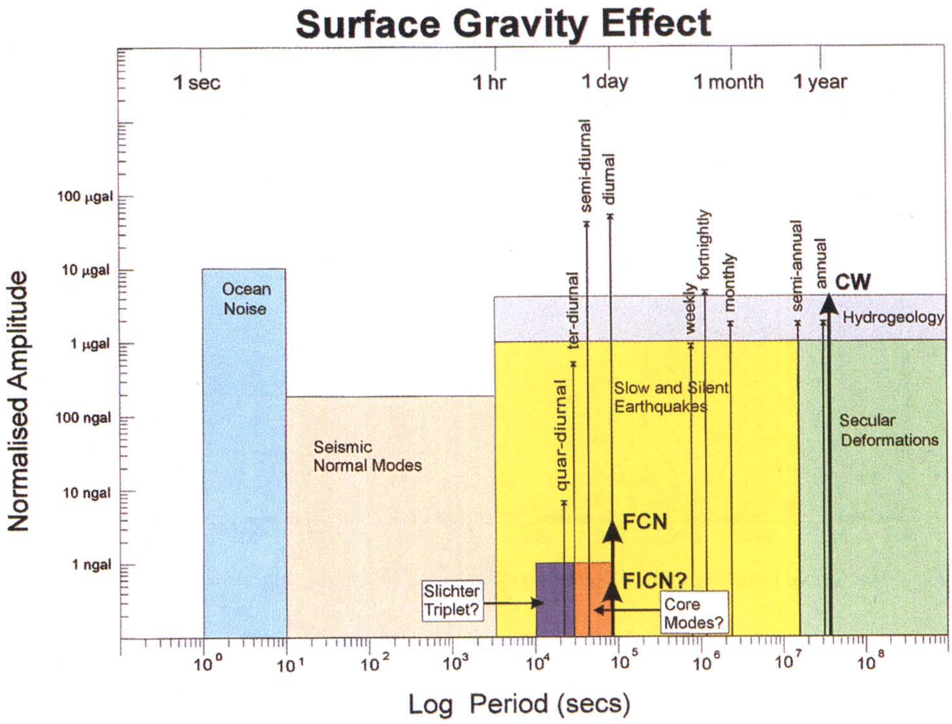


Fig. 3. Representation of the gravimetric effect of various signals at midlatitudes, using harmonic amplitude normalization. The atmospheric pressure effect is omitted because the amplitude of the background variability is dependent on the record length. Likewise, ocean tidal loading, also not shown, is highly station-dependent. Both of these signals have significant strength at tidal line frequencies.

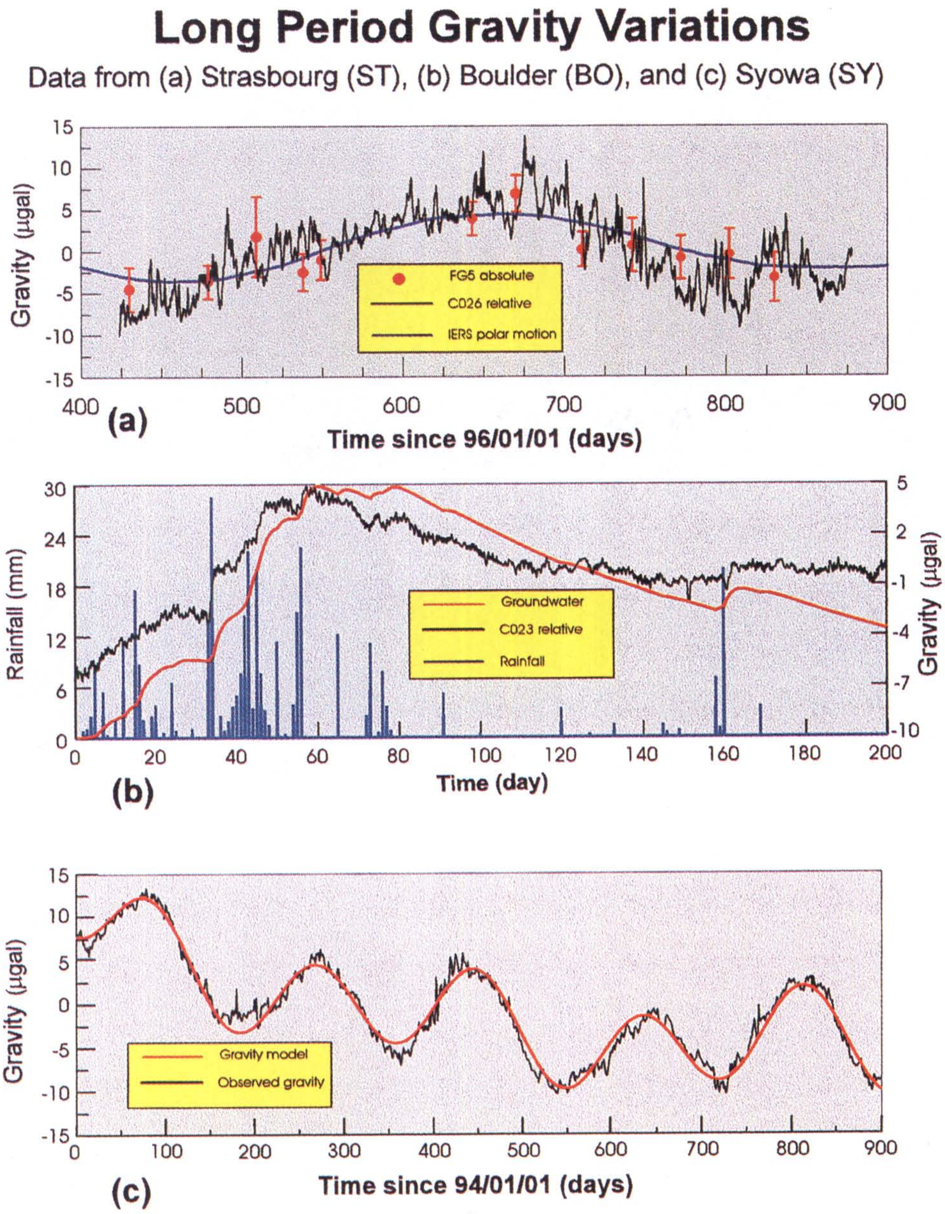
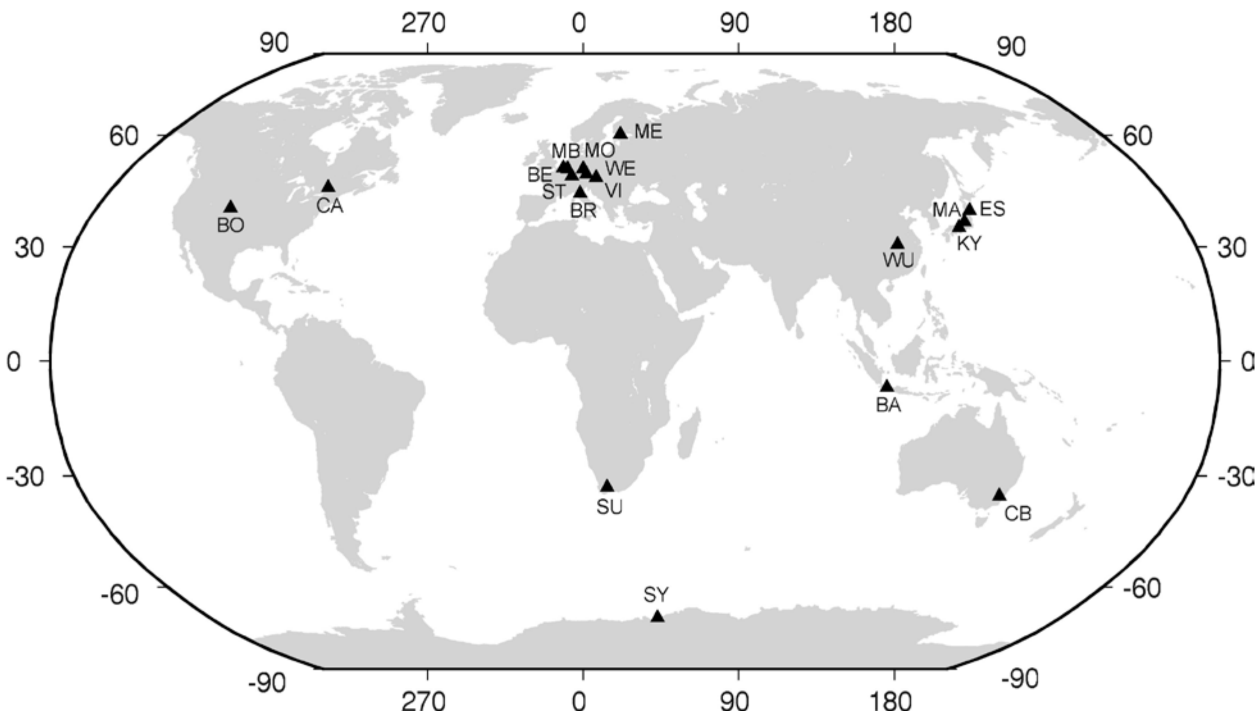
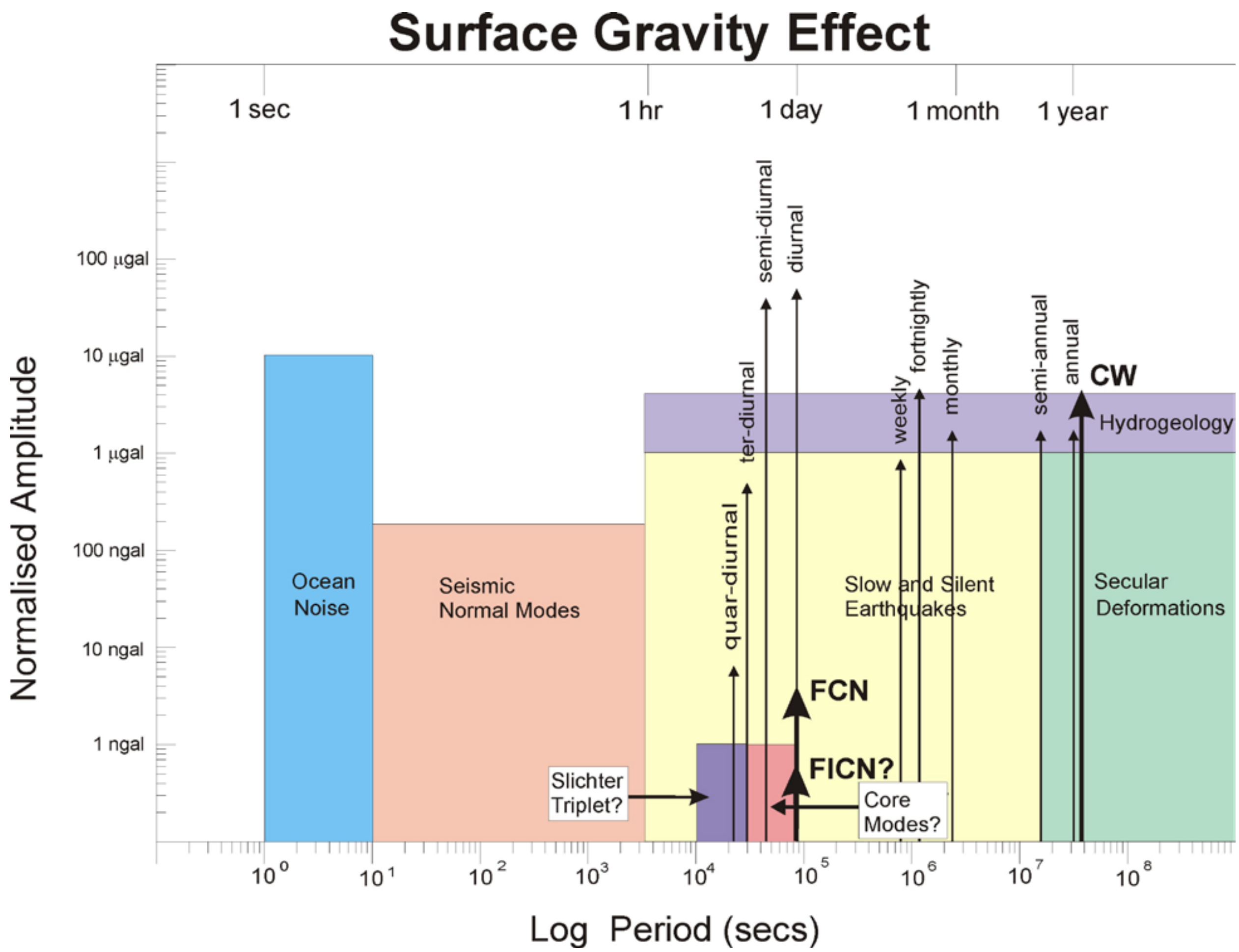


Fig. 4. Examples of long period gravity variations determined by SGs. a) Five hundred days from Strasbourg, France (ST; see Figure 2), showing agreement between International Earth Rotation Service polar motion, SG, and absolute gravimeter data; b) 200 days from Boulder, Colorado (BO), showing how rainfall and computed groundwater can account for significant gravity changes; and c) 900 days from the Syowa station, Antarctica (SY), showing that long-term gravity changes can be well modeled.


GWR
INSTRUMENTS, INC

GGP Global Geodynamics Project 1997 - 2003
Network of Superconducting Gravimeters

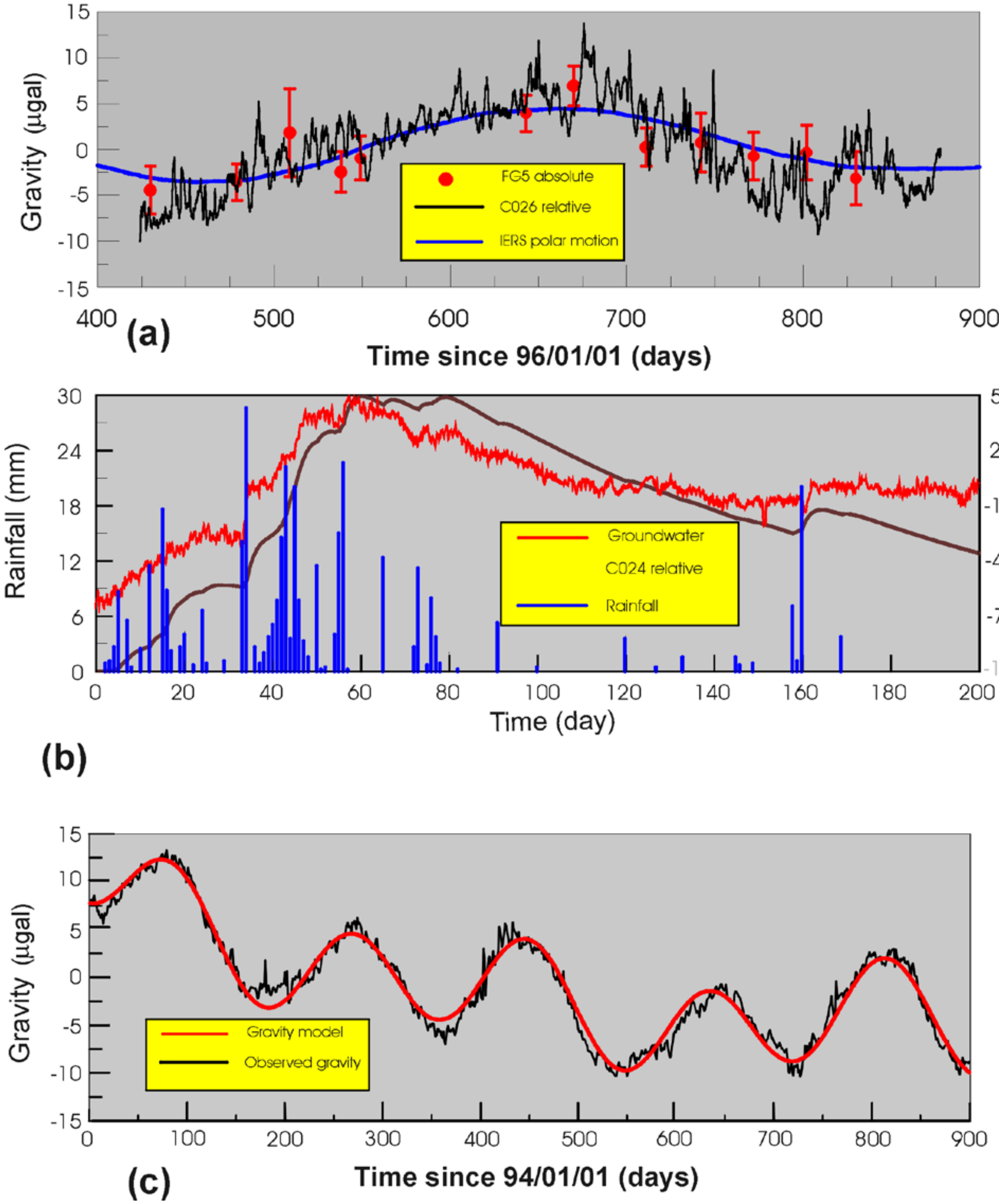


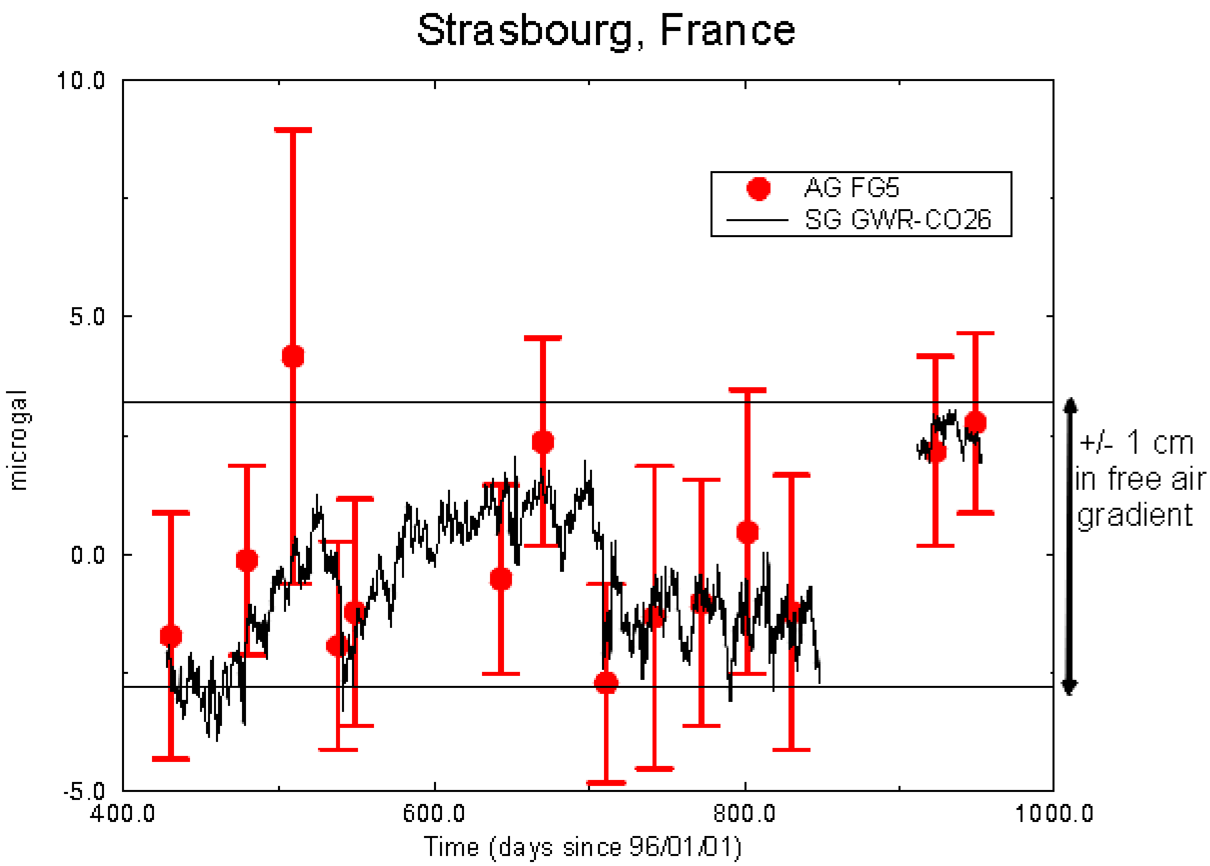


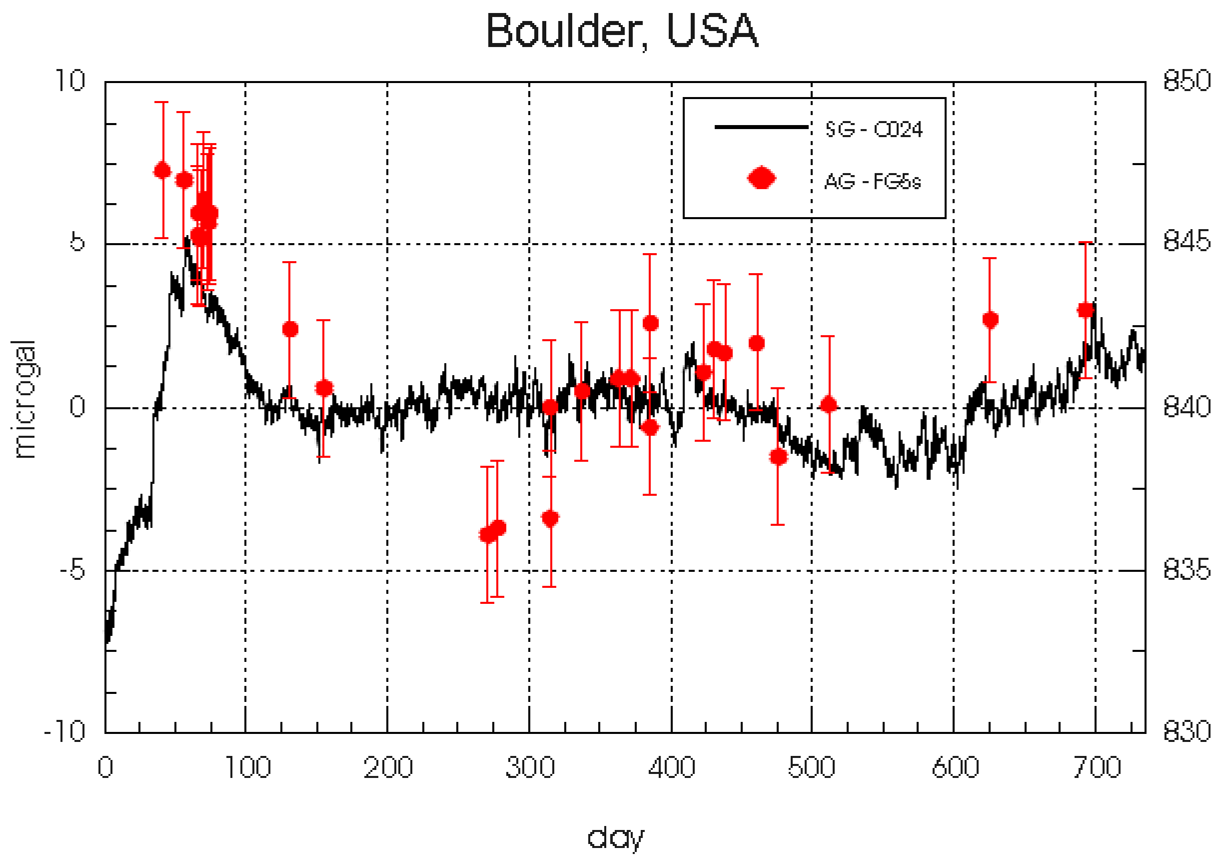
Surface Gravity Effect
1 sec
1 hr
1 day
1 month
1 year
100 µgal
10 µgal
1 µgal
100 ngal
10 ngal
1 ngal
Normalised Amplitude
semi-diurnal
diurnal
fortnightly
monthly
weekly
semi-annual
annual
CW
Hydrogeology
ter-diurnal
quar-diurnal
Ocean Noise
Seismic Normal Modes
Slow and Silent Earthquakes
Secular Deformations
FCN
FICN?
Slichter Triplet?
Core Modes?
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Log Period (secs)

Long Period Gravity Variations

Data from (a) Strasbourg (ST), (b) Boulder (BO), and (c) Syowa (SY)




Strasbourg, France
10.0
5.0
0.0
-5.0
microgal
400.0
600.0
800.0
1000.0
Time (days since 96/01/01)
AG FG5
SG GWR-CO26
+/- 1 cm
in free air
gradient



Boulder, USA
microgal
day
SG - C024
AG - FG5s
10
5
0
-5
-10
850
845
840
835
830
0
100
200
300
400
500
600
700