ESA Coastal Sea Level meeting Synthesis Report

Prepared by Chris W. Hughes on behalf of the participants, 15 Oct 2013.

This report summarizes the conclusions of a meeting sponsored by ESA and held at ESTEC, 30 September to 1 October 2013. The aim of the meeting was to discuss possible methods of connecting satellite measurements related to sea level (mean sea surface and geoid) to coastal measurements. Under discussion was the connection of tide gauges into a consistent reference frame, the extension of satellite altimetry measurements closer to the coast, and the use of complementary measurements to enhance the knowledge of the geoid at small scales, necessary to produce a truly coastal geoid measurement. In addition to discussing the technical issues, the meeting discussed the scientific and societal drivers for such a project, with a view to making the case for a future ESA-funded study.

Attendees

European Space Agency
Roger Haagmans
Michael Kern
Diego Fernández
Craig Donlon
Christian Siemes
HSU Study Team
Christian Gerlach, Academy of Science, Munich
Thomas Gruber, IAPG, Technical University Munich
Elena Rangelova, Geomatics Engineering, University of Calgary
Axel Rülke, Bundesamt für Kartographie und Geodäsie, Frankfurt/Main
Chris Hughes, National Oceanography Centre, Liverpool
Philip Woodworth, National Oceanography Centre, Liverpool
Invited Participants
Ole Andersen, DTU Space, Copenhagen
Christine Gommenginger, National Oceanography Centre, Southampton
Médéric Gravelle, University of La Rochelle
Johnny Johannessen, NERSC, Bergen
Caroline Katsman, KNMI, Netherlands
Per Knudsen, DTU Space, Copenhagen
Marie-Hélène Rio, CLS, Toulouse
Tilo Schöne, GFZ Potsdam
Ernst Schrama, TU Delft
Keith Thompson, Dalhousie University, Halifax
Wouter van der Wal, TU Delft
George Vergos, Aristotle University of Thessaloniki
Bert Vermeersen, TU Delft & NIOZ-Texel

Meeting outcome

Introduction

The central issue is the definition of a Mean Ocean Dynamic Topography (MODT) at the coast. The MODT represents the deviation of the ocean from a level surface (the geoid), as a result of ocean dynamics. Satellite gravity missions, particularly NASA/DLR's GRACE and ESA's GOCE mission, have ensured that the level reference surface, the geoid, is known to an accuracy of a few cm on length scales longer than about 100 km. Satellite altimetry missions, such as Topex/Poseidon, the Jason missions, ERS, Envisat and Cryosat, have measured the mean position of the sea surface (MSS) over most of the ocean to a similar accuracy. Thus, the MODT is well-defined over most of the ocean, on length scales longer than 100 km.

However, the most immediate societal impact of sea level comes through its impact at the coast. This is precisely where the satellite measurements are at their weakest. The influence of the land-ocean transition (both continental and at islands) means that altimetry typically ends a few tens of kilometres from the coast although better algorithms together with data from Cryosat-2 and future missions will improve on this. Sea level variability in shallow water tends to include much greater high frequency variability than in the open ocean, meaning that the temporal sampling of altimetry (typically ten days or longer between measurements) results in a less-representative mean value in these regions. The need to consider the geoid as an average over 100 km or more, coupled with the impossibility of averaging the MSS over an area centred on the coast, also means that the combination of the MSS with the geoid is less well-determined at the coast than in the open ocean. Finally, the MODT itself can have large gradients near the coast: the coast is a boundary, and many processes are enhanced at boundaries, leading often to significant differences between the MODT at, and near, the coast. There are, therefore, significant difficulties in using the satellite datasets in the very region where this information would be most useful.

Based to a large extent on the results of the preceding ESA-funded Height System Unification study, it is clear that there are two extremely different regional cases to be considered. Various lines of evidence have converged to show that, in well-surveyed regions with good in-situ gravity and levelling measurements on land, the combination of GOCE satellite gravity measurements with local information makes it possible to define the geoid height at a point (such as a tide gauge) to an accuracy better than 6 cm. On the other hand, in poorly-surveyed regions, while GOCE can provide accuracy of a few cm for the geoid when averaged over a region of radius about 100 km, there is a dearth of information on the smaller scales. The importance of these smaller scales can vary enormously from region to region depending on geological structure. For example, at some mid-ocean islands it can lead to uncertainties in the geoid at a point of several metres (typically a few dm for Mediterranean islands), whereas in regions of smooth geoid (for example parts of western coastal Canada), the small scales only appear to contribute a few cm. This issue dominates what can be done to such an extent that our ideas must be built around these two distinct cases – well-surveyed and poorly-surveyed regions.

Science Drivers and Societal Need.

The measurement of practical importance is Relative Sea Level (RSL), by which we mean sea level relative to land. It is changes in RSL that matter for issues such as extreme sea level events and the coastal flooding they cause. It is also RSL that determines whether the water is deep enough for a ship to navigate in coastal waters. Tide gauges directly measure RSL, thus providing precisely the information which is needed. However, these are relatively sparse, point measurements. The difficulty appears when we need to extrapolate these measurements in space or time. To do such an extrapolation effectively, requires that we understand the physical processes involved and their natural length and time scales, as well as their probable response to climate change.

As an example, if a global climate model predicts a regional pattern of sea level rise, that pattern represents a change in MODT (such models do not consider changes in gravity field or vertical land movement). Global climate models tend to be run at relatively coarse resolution, meaning they do not resolve fine-scale coastal processes. Indeed, they often do not have a good representation of major boundary currents such as the Gulf Stream, across which there is a sea level (MODT) drop of more than 1 metre. The primary balance of interior ocean flows is geostrophic balance, in which the flow is perpendicular to the MODT gradient. The coastal MODT clearly cannot be in geostrophic balance, as there can be no mean flow across the coast. This means that quite subtle effects must be responsible for the variation in MODT along the coast. This difference in physics is manifested in alongshore MODT variability which is more gradual (spatially) than typical mid-ocean variability. We see this, for example, in the reduced influence of the Gulf Stream at the coast, and in the much smoother coastal MODT variability predicted in the Mediterranean when drifter data are added to the large-scale satellite information, permitting the resolution of near-coastal recirculations.

Prediction of the coastal effects of the large-scale patterns predicted by climate models therefore requires “downscaling”, in which we use higher resolution models to fill in the near-boundary dynamics. Trust in such downscaling requires us to trust that the higher resolution models are accurately representing the physical processes on multidecadal time scales. This represents longer time scales than can be verified by time series analysis of model and observations; the only meaningful test of a model on such long time scales is whether it measures the spatial pattern of the time average – the MODT – correctly. In order to test this, we need to have measurements from tide gauges in the same vertical reference frame (and relative to the same level surface) as the satellite measurements offshore, so they can be dynamically connected.

A second example concerns prediction of the spatial extent of flooding from an extreme event. The statistics of coastal sea level variability will be determined from a coastal tide gauge, and so the relevant vertical reference point (datum) is the land datum relative to which the tide gauge measures sea level. The models which predict subsequent flooding, however, will rely on a local Digital Elevation Model (DEM) describing the regional topography in detail. In order to connect these, the reference level of the DEM must be connected to the tide gauge datum, requiring knowledge of the regional geoid and its value at the tide gauge. Some DEMs are already tied to tide gauge datums via the local levelling network, but a method must be found to make the connection in regions where that is not the case.

A third example concerns extrapolation of sea level data from tide gauges to other regions, either along the coast or offshore (the latter being relevant for navigation). If the information from tide gauges is to be useful in more distant coastal regions then such extrapolation is necessary. Because the dynamic topography (MODT) tends to vary more smoothly along the coast than does the geoid, it makes sense to interpolate the MODT itself rather than the geoid and MSS individually, but in order to do this it is necessary to know the MODT at the tide gauges.

Finally, a special case concerns high latitude regions where sea ice makes satellite altimetry measurements more difficult (though Cryosat-2 is promising in this regard), and the oceans are playing an important role in determining the fate of ice-sheets and ocean-terminating glaciers. In these regions, even relatively rough geodetic ties of tide gauges could be valuable. For example, the Antarctic Circumpolar Current is regularly highlighted as the region of greatest ocean uncertainty in climate models and even such a basic parameter as its mean volume transport remains poorly-determined (errors are estimated at between 10 and 30%). Knowledge of the MODT at just a single Antarctic tide gauge could provide a significant constraint on this current as a test for developing ocean models. Similarly, the Greenland coastal current is an important factor in the connection of the North Atlantic and Arctic oceans, and on the ocean heat being delivered to glaciers around the continent. Any constraint on such currents which can be derived from a knowledge of the MODT at just one of two tide gauges would be valuable.

Thus, while the new satellite observations we now have access to have dramatically improved our knowledge of the global MODT, exploiting that information for practical coastal applications requires that we find a way to bridge the gap between the satellite observations and truly coastal sea level as measured by tide gauges.

Ways forward

1) Tide gauge positioning.

Tide gauges have tradionally focussed on temporal changes in sea level (e.g. tides and storm surges and changes in MSL), and on providing individual national datums for conventional land surveying, rather than on the study of spatial differences in dynamic topography per se. As seen elsewhere in this report, while tide gauges may be connected to national levelling systems (and in some cases in fact may define those systems), there are many examples where they are not connected to nearby GPS stations, thereby precluding the expression of sea levels as ellipsoidal heights. As a result, although there is strict control of the land-based datum relative to which sea level is measured, there is a limited number of tide gauges for which the ellipsoidal height of that datum is known.

As part of the HSU study, a number of tide gauges around the North Atlantic, Mediterranean, and eastern North Pacific have been identified for which GPS positioning information with appropriate levelling ties allows the ellipsoidal height of the datum to be determined. In the SONEL global database of GPS measurements of vertical land movement within 15 km of tide gauges, there are 60 with known connections to nearby GPS, many on islands, although this does not include all those recently found for the HSU study. There are some 200 gauges with GPS time series measurements from a site within 1 km, but most of these do not have levelling ties. Any future project would have to either work with the relatively small number that already have GPS ties, or seek to extend that number.

There are two ways forward on this issue. A simple approach would be to visit a series of tide gauges, identify the relevant datum, and make continuous GPS measurements for a day or so on site (together with an appropriate link with the tide gauge datum). This is the substance of Philip Woodworth's ELLIP-C proposal, which suggests an appropriate number of tide gauges to be of order 600 (twice the 300 in the GLOSS network), although this number would take time to reach.

The second method is to work to ensure that the relevant agencies in each country coordinate their activity and ensure that the tide gauge datums are linked into the national levelling networks. Although this may be the ideal long-term solution, it has proved difficult to achieve in the past, and rapid progress should not be expected.

2) Regional gravity

Even where the ellipsoidal height of the tide gauge datum is known, making a dynamical connection (linking MODTs) to the open ocean, or to DEMs for flood modelling, requires knowledge of the geoid at the tide gauge. This implies a means of adding small-scale information to the 100 km averages available from satellite data.

The ideal situation requires terrestrial and/or airborne gravity measurements over a region surrounding the tide gauge, and a combined solution of the satellite and regional measurements. Where good land-based in-situ gravity measurements are available, these can be used to provide small-scale geoid information inland of the tide gauge, but they can only ever be available in the land half-space around the tide gauge. They can be complemented by gravity anomalies derived from satellite altimetry, but at the expense of losing information about the MODT close to the tide gauge (altimetry measures a combination of the geoid and the MODT meaning that the MODT would contaminate the inferred gravity anomalies). They can also be complemented by marine gravity measurements, where they are available.

Where a tide gauge is tied into a local levelling network with good GPS ties, this can be used to improve the value of the geoid at the tide gauge by using levelling information as a measure of small scale geoid undulations, linked into satellite gravity over land at the larger scale. Even without such a tie, the levelling information can give a good guide to how rough the geoid is in that region, and hence the expected size of errors due to the lack of small scale information.

In regions where there is no nearby in-situ gravity, and no geodetic tie to a strong, GPS-linked levelling network, the best that can be done is to use a DEM, together with assumptions about rock density and dynamical compensation, to infer the small-scale geoid undulations. This can typically explain 60-70% of the small scale undulation signal. Whether this leaves errors of a few cm or more than a metre depends on the particular site.

Where geodetic methods cannot produce a good measure of the geoid, a possibility is to turn to oceanographic levelling. This means using regional ocean models and/or independent measurements of currents (e.g. from drifters) to determine the small-scale MODT, and thus to connect the measured large-scale offshore MODT to that at the tide gauge, thus indirectly determining the geopotential height of the tide gauge datum without needing to measure its ellipsoidal height and the local geoid height separately. This method makes it impossible to validate the ocean model at such sites, but if a model was validated at well-measured sites it could be used to link-in tide gauges at poorly-measured sites.

Thus we have three levels of options. 1) Fly airborne gravity missions over coastal regions around the world – the ideal long-term solution, but expensive and unlikely to be practical on a short time scale. 2) Use tailored solutions to sites around the world with good gravity and/or levelling information to produce local information at a set of sites determined by present availability of data. 3) Extend the tied tide gauge network by a combination of oceanographic levelling using models validated in well-measured regions, and selected sites where the small-scale geoid signal is small. In all cases, the extension of accurate altimetry measurements closer to the tide gauge will help, by reducing the size of the gap that is to be bridged.

Summary

The most important impacts of sea level occur at and near the coast, but connection of satellite measurements to coastal measurements (tide gauges) is problematic for two reasons: the satellite MSS and geoid measurements are least reliable and hardest to exploit near the coast, and the special dynamical character of along-shore MODT variations means that coastal MODT can be quite different from near-coastal MODT. Exploitation of what we have learned from satellite data for practical applications such as flood extent prediction, navigation, and climate projections of the ocean dynamic contribution to sea level change, require that we connect the satellite observations to coastal systems, and connect coastal to land systems.

In well-mapped regions with good levelling, gravity data, and GPS measurements, it is possible to combine satellite gravity with in-situ geodetic data to make this tie to better than 6 cm. Dedicated solutions may be needed. In some regions where the relevant data are proprietary, it may be the case that regional geoid solutions are available and can be combined with satellite data to approach the same accuracy. In such regions, the resulting MODT at tide gauges can be used to validate regional ocean models and ensure that they are capable of modelling the processes which set up the along-shore MODT variations.

In poorly-mapped regions, combination of DEM information with satellite data can improve knowledge of the geoid at tide gauges, but to a degree which needs to be studied on a site-by-site basis. In such regions, it is likely that oceanographic levelling using regional models and/or additional observations (such as drifter data) to fill the gap between open ocean and coast will provide the best tie, with geodetic methods providing a coarser validation (probably 10 cm or more). For global-scale variations in the coastal MODT, and especially in the particular case of Antarctica, such accuracy is still a useful check on the climate model plus downscaling approach to coastal predictions.

A limiting factor is the number of tide gauges with tied GPS measurements. Any additional ties could greatly expand the geographical range over which the analysis can be undertaken, and would improve reliability (simply by increasing the currently small number of sites available). An ESA endorsement of the importance of such activities would be welcome, to encourage the adoption of such a campaign as a GLOSS activity.

In all regions, improvements can be made by using new methods to extend altimetric MSS measurements closer to the coast.

A more ambitious, long-term plan would involve coastal airborne gravity campaigns at sites around the world, systematic GPS measurements at a much larger set of tide gauges (with proper ties to the tide gauge datum), and work to coordinate the mapping agencies and agencies responsible for tide gauge maintenance around the world, so that tide gauge datums are connected to national levelling networks.

Glossary

DEM = Digital Elevation Model: a map of the geometry of the earth’s solid surface. Properly, such a map would be measured relative to the geoid (thus being analogous to the MODT), but the sources of such information may be geometrical and hence analogous to the MSS, with separate knowledge of the geoid required.

Ellipsoidal height: The height measured relative to a known reference ellipsoid embedded in the earth, a purely geometric quantity with no gravity information required.

Geoid = a particular gravity equipotential surface, being the shape the sea surface would tend to adopt in the absence of any external forces acting, after any flowing currents had been damped out.

MODT = Mean Ocean Dynamic Topography: the height of the MSS above the geoid. A sloping MODT requires that there be currents flowing in the ocean and/or external forces acting.

MSS = Mean Sea Surface: a time-averaged map of the position of the sea surface measured relative to the centre of the earth.

Appendix: Notes from the ESTEC meeting

Roger Haagmans

J Geodesy 85 11 (2011) GOCE processing special issue

Release 5 expected mid 2014

GOCE currently approx 225 km, running out of fuel 2nd half Oct, expected end of life around 2nd half Nov.

STSE (support to science element) studies: Atmos density, time variations, earth crust and upper mapping, exploration of geo-resource, unification of height systems.

Ramon Hanssen study combining gravity, GPS, SAR looking at VLM over large area.

Include Harvest platform tide gauge to connect TG to altimetric reference system?

Thomas Gruber

Introduced HSU participants. www.goceplushsu.eu. Project overview. Large-scale errors from comparison of GPS+Levelling with GOCE geoid. Described omission error (~20-30 cm beyond degree 200). Effect on countrywide average variable 1-10 cm approx. Well-surveyed vs. poorly-surveyed areas. Mt Everest example.

Using GPS+Levelling in the region surrounding a tide gauge produces 1) a way to link TG to the geoid averaged over a wider region and beat down omission error. 2) a way to estimate how smooth the geoid is in the surrounding region, and therefore how large the omission error is likely to be – a method to select good TG sites.

Discussion: Is GOCE being used in preference to EGM08 (for MODT determination)? Per Knudsen – yes. Comments on problems of gluing together coefficients from different models, and gain from calculating solution using in-situ gravity + satellite simultaneously.

Axel Rülke

POLCOMS/LivMIT European unification using TG: Differences up to 5 cm between models for country averages.

3 different approaches all agree at 5-10 cm (oceanographic, levelling, gravity field).

Germany levelling vs gravity field agrees to 1.7 cm rms.

Elena Rangelova

GOCE correction in Canada makes clear the GIA pattern resulting from levelling being many decades old.

NAVRS North American Vertical Reference System, 2022 will be geoid based. Target 1-2 cm at coast, 3-5 cm in mountainous areas.

GOCE improvement – small in Canada, but 2 cm to degree 200 in Mexico and Alaska. Mexico improvement extends to degree 240.

GOCE: No improvement in well-surveyed areas. No visible improvement in mountainous areas where dominant error is small length scale. 20-30 cm improvement in areas with little gravity data.

Techniques for dealing with geoid bias introduced by gravity data in different datum systems, reduce from decimetres to < 1 cm.

Consider time dependence of geoid – can locally be large (1cm/decade at most). Almost everywhere < 0.5 mm/yr (cm/decade).

Philip Woodworth

Data needed: MSL from tide gauges with respect to benchmark; Ellipsoidal height of benchmark;

~30 points on European coastline, ~20 in Med.

GLOSS core network ~300 TG. Two-thirds have nearby GPS. Only 14% have good ties between GPS & benchmark. Because GLOSS mainly interested in rates. Who is responsible for ties? Geodetic or TG people?

Need someone to spend 2 days with GPS at each TG site.

Would like ESA to express interest to GLOSS - get this accepted as GLOSS activity for next 2 years.

Roger comment – can tell us about processes near coast. Johnny: bathymetry important in shallow water.

Keith Thompson

Simon Higginson papers.

Altimetry/spectrally-nudged NEMO/surface drifters very good agreement in GS region.

Sea level at coast relative to CGG2010: Very Flat along coast except a few places where there are jumps.

Geostrophic balance doesn't hold, and idea of a steric change becomes meaningless. Quite different physics.

Strongest coastal signals from tide gauges on distinct coastlines and islands.

Coast acts as low wavenumber filter on sea level.

More challenging to extract ocean information from gauges on same coastline. Require accuracy better than 5 cm. Models capable of resolving many different processes -2-way nesting or variable grid models.

MH-Rio: For model constraint may need to have complete Dyn Top, not just currents.

Discussion

CWH: Need to identify the physics questions which can be addressed by mean dynamic topography at TG. Immediate impact of sea level is via flooding at the coast. Do climate models address the processes responsible for this? Certainly don't have very local coastal processes, or wave set up, and so cannot address possible changes in these. If we wish to verify that models are capable of capturing the processes which are responsible for sea level changes on time scales longer than we have measurements for, we have to use the mean dynamic topography and ask whether the models can reproduce that. Also issues of filtering – smooth as little as possible where gradients are large, but more smoothing is appropriate in regions where dynamic topography has less small scale structure. Clear in open ocean, equally true in coastal regions?

Christian Gerlach: GOCE+regional geoid and European TGs produces Dyn Top which agrees with models to 5.5 cm RMS (improvement over 6 cm with pre-GOCE data). Comparison with DTU+GOCE: 13-14 cm (NB not-truly collocated with tide gauges, so larger errors to be expected).

Johnny: Norwegian coastal current important for coastal sea level. Also river runoff. GPS ties to tide gauges important for future altimeter missions. Particular issues in polar regions.

Phil: Greenland melt also -> narrow coastal current. Suggests for dynamic topography (cf florida current) would like more like 600 TGs, rather than the 300 of the GLOSS network.

Médéric: of 300 GLOSS gauges, about 2/3 have nearby GPS records, but only about 14% have geodetic ties to those records. Problem is one of responsibility – in most countries, a maritime agency has responsibility for maintenance of TGs and benchmarks, and a geodetic survey agency has responsibility for levelling between national network benchmarks, but no-one take responsibility for connecting the two.

Roger: Is it clear that tide gauges and altimetry produce the same "mean sea level"?

Keith: TGs much better at resolving large amplitude, high frequency variability; better time averages more rapidly.

Ole: Some altimeters (inc Sentinel) are sun-synchronous and will therefore result in a permanent difference between altimetric mean and TG mean because of aliased S2 tide. Altim coastal accuracy probably also limited to around 5 cm, partly because of MSS measurement, but also because of geoid omission error.

Christine: Has anyone looked at whether near-coastal altimetry is sufficient to act as a surrogate tide gauge?

Craig: SAR altimetry is getting closer to the coast, but processes there become more complicated – eg waves have different character from deep ocean which is the source of most data for empirical sea state bias correction. Could use satellite data as QC for tide gauge datum accuracy. Could we also be looking at issues with local configurations of tide gauges – are they sampling wider ocean or local processes?

Roger: large discrepancy among models of ACC means data could be a strong constraint. Cwh: true but most of that can come from open ocean measurements. However, there is significant uncertainly remaining, associated with near coastal sea level signals.

George: The dynamic topography of the Mediterranean spans a range of about +-10 cm, and flows through straits typically lead to 1 cm changes, so 5 cm accuracy would be of little use. Perhaps flow measurements could provide constraints on dynamic topography to help connect datums of islands?

Keith: for coastal flooding there is an important issue of how to connect tide gauge information to DEM data – also requires GPS determination of ellipsoidal heights of TG benchmarks.

Marie-Hélène Rio: Isotropic filtering has limitations. Uses instead an ocean model to predict covariance structures in x and y as a function of region, combined with a priori observational errors, to produce optimally-filtered MODT, though still limited to length scales > 100 km.

Adds information from drifters combined with satellite altimetry to help define near-coastal and narrow currents. Especially noticeable in Leeuwin Current, Aleutian Current, and Agulhas/Madagascar currents. Tide gauge information would be useful as a way of integrating across such currents to provide a good estimate of total near-surface transport.

Comparison of geodetic currents with drifters shows more disagreement in shallow water (< 500 m).

Mediterranean mapping – drifters make a large difference, showing that the Ligurian Gyre closes with a coastal current along the northern boundary. This makes ~10 cm difference to the coastal sea level. Pattern when drifters are used shows less variability along boundaries.

Christine Gommenginger: Improvements in coastal altimetry. Wet troposphere correction, typical error was ~15-20 cm, but using GNSS-derived products this can be reduced to ~1-2 cm. Waveform retracking is leading to more good values near the coast, though there are many methods and no agreed “best” approach. Cryosat SAR mode allows close approach (hundreds of metres) to the coast when track is perpendicular to the coastline, and reduces 1 Hz instrument errors from 1.6 cm to 1 cm. Cryosat comparisons with tide gauges give RMS errors of 8.2 cm (Venice) and 20 cm (Helgoland), but note that there is not yet a sea state bias correction to apply.

George Vergos: Many Greek islands, as is the case globally as well, are not geodetically tied to the Greek datum at Piraeus so a local TG MSL connection to the country zero level and/or a global geoid is needed (also to tie their measurements with other TGs for coastal processes). MODT from GOCE cannot explain the deviation between the local MSL and the levelling origin, due to MODT problems close to the coastline and inherent geoid/levelling errors. Gravity data in region is usually proprietary, but can be used under license. Accuracy given as 2-5 mGal, but actually appears to be 6-9 mGal. There is usually no tie between tide gauge benchmarks and the levelling network. Presented some results for Gavdos (small island south of Crete) which is being used for ENIVSAT, Jason-1, Jason-2, HY-2 (Altika and Sentinel

3 in the future) cal/val. Small-scale geoid is a big issue, with GOCE MODT helping but high-frequency geoid features can only be resolved by gravity (to use the TG MSL for cal/val, coastal processes, etc.). Connection of tide gauges to altimetry is helped if altimetry reaches closer to the coast. Otherwise, airborne gravity and buoy campaigns are needed.

Ole Andersen: BLAST = Bringing Land And Sea Together, VORF = Vertical Offshore Reference Frame, concerned with defining the mean sea surface and LAT = Lowest Astronomical Tide, to link to chart datum. Approach is to use regional geoid to connect altimetry to tide gauges. Note – bathymetry on charts is relative to LAT, often not appreciated by modellers.

There are > 200 offshore tide gauges in the North Sea (usually short records on drilling platforms).

Must take care not to use inverse-barometer corrected sea level when making connection to tide gauges.

Comparison of extrapolated DNSC08 MSS with (Marek Ziebart) 320 GPS-measured tide gauges around Britain, gives agreement of mean to 1.24 cm and standard deviation 6.8 cm. Upgrading to DTU10 MSS improves mean to 0.11 cm.

In the English Channel, LAT is more than 2.5 m below MSS. There are several cm discontinuities in LAT between different countries, due to use of different tide models.

Médéric Gravelle: SONEL focuses on GPS time series within 15 km of a tide gauge. Web site combines GPS vertical land motion trends with tide gauge trends from PSMSL to offer both geocentric and relative sea level trends. 60 tide gauges are in the database with known connections to GPS, many on islands (this excludes N American values collected by Phil). Around 200 tide gauges have a GPS site within 1 km. There can be difficulties in identifying which benchmark is being used by different agencies and at different times.

Johnny Johannessen (by email): Regarding the regional differences/characteristics we are up to with MSL it might be necessary to make an approach to the challenge with this in mind. Hence the Mediterranean, the Polar Ocean, the Antarctic Circumpolar Current, the Agulhas Current and the global coastal MSL (Fig shown several times today) are possible good candidates. Regarding the Agulhas the signal there is very strong, the current is on the coast to the northeast and then diverge from the coast and follows the shelf break from Durban southwestwards. SAR altimeter performance (Cryosat and Sentinel-3) in this area would therefore be very interesting to explore further. This is also where I am involved with range Doppler velocity from Synthetic Aperture Radar - SAR (Sentinel-1) which is an interesting complement to (GOCE + alt) ADT and inverted geostrophic current.

Agenda for Tuesday:

Short talks by those who have slides to present: Marie-Helene Rio, Christine Gommenginger, George Vergos, Mederic Gravelle

Split into splinter groups (free-form… switch between groups)

Lunch 12:30-13:30

Return to plenary and collectively summarize answers to questions, plus any other points raised.

Splinter group 1: Minimizing Omission Error

- What are the omission errors due to missing small scale geoid information when using just GOCE, and how spatially variable are they?
- Where is there good in-situ gravity data, and what are the prospects for incorporating that data?
- What can be done where there is no good in-situ gravity?
- Are there regions where near-coastal spatial averages of the dynamic topography would be sufficient? How broad a region must be averaged to bring errors down to (say) 2 cm, 5cm?
- Reference frame issues – how do we relate sea level determinations to chart datum?
- What special considerations must be made for small islands?
- Can we synthesize the possibilities for different sites around the world?

Splinter group 2: Coastal altimetry and altimeter absolute calibration

- What is a realistic accuracy for coastal altimetry at various distances from the coast?
- Can the addition of many extra sites overcome the disadvantage of no true collocation?
- Can altimetry on the continental shelf produce better measurements than a combination of deep water altimetry and coastal modelling?
- Can absolute dynamic topography from tide gauge measurements contribute to an assessment of the accuracy of coastal altimetry?
- Can we summarize the potential gains from and for coastal altimetry?

Splinter Group 1 Summary (Thomas Gruber)

1. What are the omission errors due to missing small scale geoid information when just GOCE is used and how spatially variable are they?

Omission error in a global average is at a level of several dm (e.g. 30 cm). It varies significantly from site to site depending on the topography, the geology and other factors. It can reach even several meters in the case of small islands for example. On the other hand in topographic and geologic smooth areas it even can be close to zero. There is no general rule to estimate the omission error above the GOCE resolution. As a simplified approach one can compute the contribution of the topography for spatial frequencies above the GOCE resolution to the geoid. This explains roughly 60% to 70% of the geoid signal in this frequency range, but disregards rock density anomalies at a point and a possible lithospheric compensation. In order to answer the question it was distinguished between two cases:

- Well surveyed areas: The omission error can be quantified with good accuracy (several cm) from EGM2008 plus residual terrain signal (above the spatial resolution of 5'x5' of EGM2008) and even better from regional high resolution geoid solutions, which are based on a global GOCE field. Here it is assumed that high quality and dense gravity information was available. An issue could be the combination of continental and marine gravity information (see also question No. 2).
- Sparsely surveyed areas: It is assumed that in such regions high resolution and high quality gravity data are not available. Therefore regional geoid solutions of sufficient accuracy are hardly available and EGM2008 also performs not good enough due to the missing data. Therefore the omission error can hardly be quantified from such models. As an alternative one could estimate the topographic effect on the geoid, which explains a larger part of the signal but not completely (see above).

2. Where is there good in-situ gravity data, and what are the prospects for incorporating these data?

- Areas with good in-situ gravity data: In many countries gravity data are kept under national or even military control and are not accessible to science applications. There are also large areas in the world where no gravity data ever have been measured or systematically collected. A good indicator where gravity data are available is shown in the data coverage map of EGM2008. These areas can be assumed to be of reasonable or good quality in EGM2008.
- Incorporating gravity data: Data are incorporated either by a global approach (e.g. EGM2008) or by regional geoid computations. When combining the GOCE global fields with regional gravity data (by whatever approach) for determination of the local geoid at a tide gauge station a few things need to be taken into account. These are:
  - The combination procedure should be tailored to coastal areas combining land and ocean gravity data. Country-wide solutions might not be optimal (e.g. depending on the size of a country).
  - Altimetric gravity might be contaminated by the DOT. When using them in a regional geoid determination they should be carefully analysed beforehand.
  - Local DOT models (from local ocean models) might be useful for the determination of coastal marine gravity anomalies.
  - High spatial resolution topography and bathymetry (ideally better than the 100 m typically available globally) can be useful for modelling small scale geoid effects.

3. What can be done where there is no good in-situ gravity?

As a first choice gravity needs to be observed. Flight campaigns in an area of a few hundred km (tbd) around the tide gauge would be a good data basis for regional geoid computation at the tide gauge. If accessible ground observations (gravity, levelling and GPS) also would be helpful, but need much more effort.

On islands apart from gravity data also GNSS/Levelling data and a good local MSS with a local DOT model would be helpful.

4. Are there regions where near-coastal spatial averages of the dynamic topography would be sufficient? How broad a region must be averaged to bring errors down to 2-5 cm?

Areas with a smooth DOT along the coast could be helpful. As an example the Canadian West coast could be a good test area. There regional geoid solutions and geoids derived from the ocean approach applying a MSS and a local DOT agree within a few cm. The size of such a region depends a lot on the DOT roughness. Also high resolution local DOT models are required. At this point we are not able to provide a rule of thumb for this.

5. Reference frame issues – How do we relate sea level determinations to chart datum?

In any case all quantities need to be brought into the same system. For this the different datum and benchmarks need to be linked to each other by high quality local ties. This specifically addresses the issue of converting the tide gauge records given for the lowest astronomical tide to the altimetric MSS, of applying the same tide system for all computations and linking the tide gauge benchmark to the levelling and GNSS networks. Also improved local tide models might be required in order to reach the envisaged accuracy.

6. What special considerations must be made for small islands?

See remarks above

7. Can we synthesize the possibilities for different sites around the world?

As a conclusion one should be able to select a set of tide gauges which fulfils the following requirements:

- good data coverage for all required quantities (specifically gravity data),
- well linked to the GNSS and levelling networks,
- good local DOT models, and
- region with small omission error.

One should be able to identify such a set of tide gauges and one could start a first attempt to link them across the oceans in order to determine height system offsets over large distances. Specific computations might be needed, which include: regional geoid determination, recomputation of altimetric gravity from local MSS and DOT models, and others.

Splinter Group 2 Summary: Christine Gommenginger

The group was asked to discuss the following questions:

- What is a realistic accuracy for coastal altimetry at various distances from the coast?
- Can the addition of many extra sites overcome the disadvantage of no true collocation?
- Can altimetry on the continental shelf produce better measurements than a combination of deep water altimetry and coastal modelling?
- Can absolute dynamic topography from tide gauge measurements contribute to an assessment of the accuracy of coastal altimetry?
- Can we summarize the potential gains from and for coastal altimetry?

It was quickly ascertained that it is not presently possible to answer the first question without considerable more work.

It was stated that, when comparing tide gauges and altimeters, one needs to be sure to use the right corrections and the right properties to perform proper comparisons, i.e. make sure the TG and the altimeter measure the same thing! One good example is Total Water Level Envelope used in instantaneous comparisons, which avoids the introduction of residual errors linked to insufficiently accurate corrections (e.g. IB correction, tides). Similarly, it was reported that the best correlation between TG and altimetry is often observed as far as 40km from the TG, which may reflect problems with corrections near the coast (e.g. wet tropospheric correction) rather than with the altimeter data per se.

It was noted that comparisons between TG and altimeters would benefit from averaging over longer time periods, e.g. looking at differences in mean values over 1 year or longer. This would remove much of the high frequency variability and reveal residual effects e.g. residuals in MSL due to non-linear tidal components in the North Sea.

The discussion then turned to the fact that not all coastal sites are equally suited to perform TG/altimeter comparisons. Specific case study areas could be selected on two accounts: 1) as representing different oceanographic regimes, where different processes have different relative importance and 2) where good in situ data and/or good modelling facilities are available.

Possible sites that were discussed included (in no particular order):

a) North Sea – challenging area for altimetry; availability of SAR altimetry data from Cryosat-2 since 2010.
b) Agulhas Current and Madagascar Strait: the Agulhas region has seen much research lately linked to currents, and the region benefits from some good tide gauges and from Cryosat-2 SAR mode altimetry since 2010. The Madagascar Strait is a region known for its very poor geoid, making it a challenging region for gravity.

c) East Australian Current and Leeuwin Current: well monitored area with good modelling, and a region where drifters showed a strong impact on the MODT (as shown in presentation by M-H Rio during the meeting)
d) South Chilean Coast: Very rapid elevation change (plus/minus 5000m) in the coastal strip makes this an extremely challenging region for gravity. Linking this region to b) and c) would enable some investigation of long distance connections.
e) Harvest platform: flat geoid, long-term cal/val site for all satellite altimeters.

TG/altimeter comparisons would need to be done for both offshore and onshore TG. However, most offshore TG are sited on islands where the geoid is problematic.

In all cases, the TG stations should have GNSS nearby, both for levelling to an absolute level and to compute better GNSS-derived wet tropospheric correction. However, this will dramatically reduce the number of suitable TG sites.

Regarding altimeter ranging error due to sea state (i.e. sea state bias), the problem could be alleviated by focussing on areas where sea state is generally low.

TG/altimeter comparisons are typically done on relative levels. The height unification system would enable those comparisons to be done on absolute levels (to put all altimeter and TG in the same frame of reference). But how soon will we have a unified height system ?

Altimeters could provide information about the high frequency content of SSH (especially with SAR altimetry). Comparisons could focus in areas with good local gravity data and where high-resolution coastal model are run (sub-km resolution). There is also some benefit in including models that can account for wave setup, which can contribute to MSL.

Additional documents can be found at http://www.goceplushsu.eu/gpweb/gc-cont.php?p=56