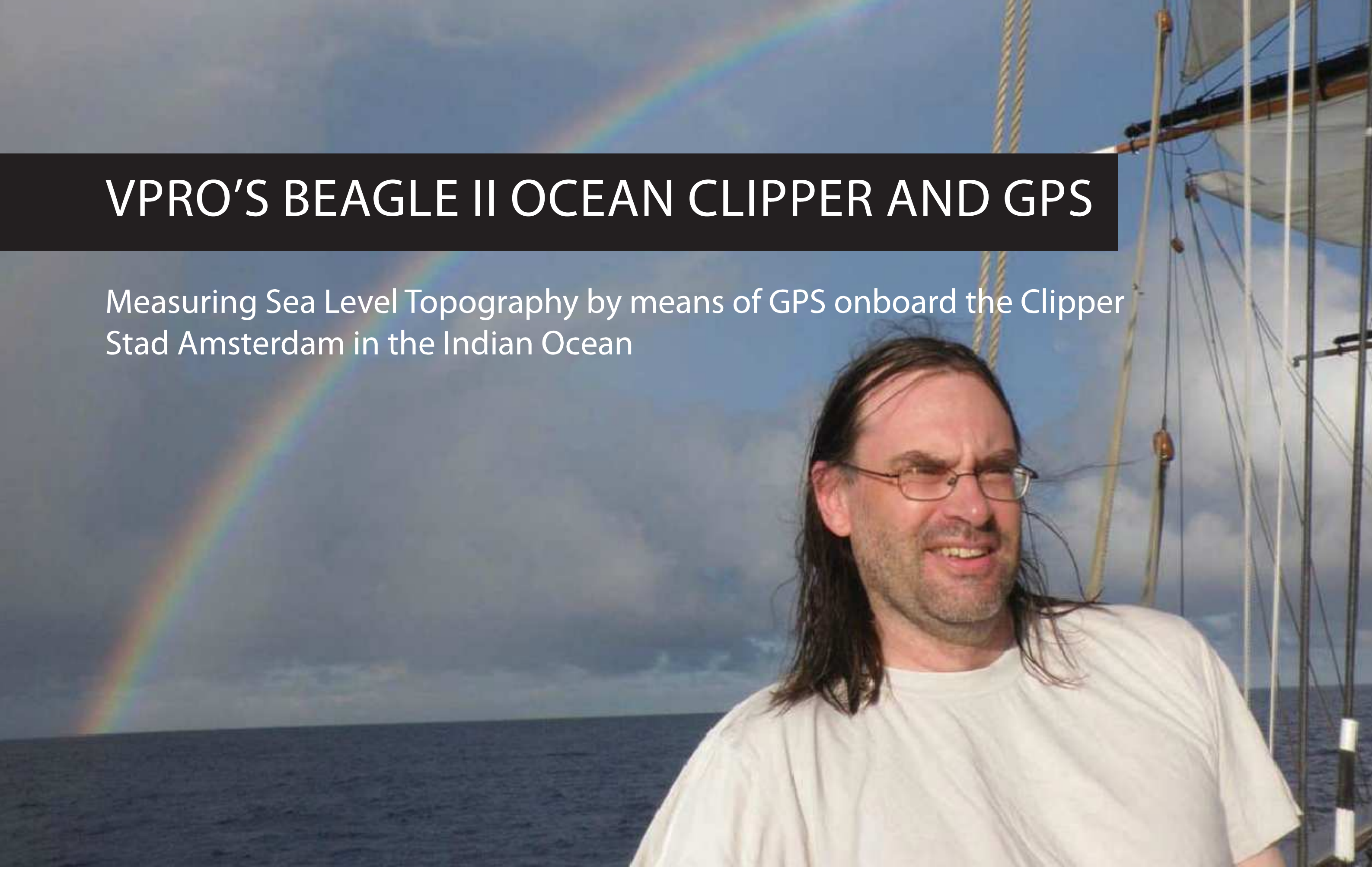

VPRO'S BEAGLE II OCEAN CLIPPER AND GPS

Measuring Sea Level Topography by means of GPS onboard the Clipper Stad Amsterdam in the Indian Ocean

From March 16 until April 5 2010 Bert Vermeersen sailed on the Clipper Stad Amsterdam from Perth (Australia) to Port Louis (Mauritius). Onboard GPS measurements were done to determine the absolute vertical position of the sea level. The sea level over the sailing track differs by several tens of meters in height. Gravity variations are the cause of this. Elsewhere (see references) the reader can find a lot of information, photos and videos of the Beagle II voyage; here we will concentrate on the measurements, preliminary measurement results and consequences for present-day sea level change due to continental ice mass variations.

TEXT **Dr. Bert Vermeersen (Associate Professor Astrodynamics & Space Missions)**
Dr. Ir. Hans van der Marel (Assistant Professor Mathematical Geodesy & Positioning)

THE BEAGLE II PROJECT – IN DARWIN'S WAKE

Early September 2009 the Dutch Clipper Stad Amsterdam (Figure 1) left the harbour of Plymouth in England following the path over the oceans of the famous journey of the H.M.S. Beagle in the 1830's. The voyage of the Beagle would turn out to be of historic scientific importance as one of its passengers, Charles Darwin, got the inspirations and data for his later theory on natural evolution over the five year trip. Leaving Portsmouth, the national Dutch television station VPRO, in collaboration with other tv stations and with science institutions like NWO (Nederlandse Organisatie voor Wetenschappelik Onderzoek) and KNAW (Koninklijke Nederlandse Academie van Wetenschappen), embarked on a one year media voyage with weekly television broadcasts and live webcams on the internet (beagle.vpro.nl). At each harbour a few scientists and artists were invited to join the team to not only discuss and talk about various aspects of Darwin's voyage, but also to look at the current state of our planet and even to do scientific experiments onboard. While Darwin gave us fundamentally new insights in the history of our species, the BEAGLE II project thus also concentrated on the future of species. On one of the tracks, from Fremantle, Western Australia (the harbour of Perth) to Port Louis, capital of the island of Mauritius on the eastcoast of Africa, one of us, Bert Vermeersen, was invited to do GPS measurements of the vertical position of the sea level. The history behind this invitation is a story on itself.

In January 2009 Bert Vermeersen was invited by the Dutch radio programme HoeZo? Radio to talk about the upcoming launch of ESA's GOCE gravity satellite. While discussing the rather difficult subject of gravity with the interviewer, the idea was borne to illustrate gravity effects on sea level by means of a hypothetical (at that time) measurement of the absolute vertical position of the sea level by means of a GPS-receiver. After all, a "TomTom at sea" is much easier to understand for the average layman than gravity, and measuring it by means of a pendulum or by GOCE. The example was given of a GPS receiver onboard a ship travelling from Spain to Turkey. Over that track the GPS-receiver should indicate that the ship would float through a valley in the sea surface of the eastern Mediterranean of about 30m. This stable valley in the sea-surface is due to missing solid-earth mass beneath the eastern Mediterranean, which in its turn is

Figure 1. The Clipper Stad Amsterdam in the harbour of Freemantle near Perth, Australia - on the left, former employee of TU Delft, Lennard Huisman, now at Curtin University, measures the distance of the GPS antenna with respect to sea level

a result of tectonic processes (subduction of lithosphere related to the collision of the African continent with the European continent). This example lead to the invitation by VPRO to take part in the Beagle II project.

IN VENING MEINESZ' WAKE

The path of the Beagle II voyage on which GPS measurements of the sea level surface height would be performed was soon estabilished. The deepest valley in the sea level surface can be found beneath India. As the original plan was that the Stad Amsterdam would cross the Indian Ocean from Fremantle, Perth to Mauritius by the Cocos/Keeling Islands, thus sailing right through this sea surface valley, the choice for the track Perth – Mauritius was rather obvious (at a later stage it was decided that the Clipper would sail straight from Perth to Mauritius, thus taking a more southerly route across the Indian Ocean). The track Fremantle – Mauritius, or rather the opposite route Mauritius – Fremantle, rings a bell in the geodetic community. Exactly 75 years earlier this track was part of one the famous voyages of Prof. Dr. Ir. F.A. Vening Meinesz onboard submarines. In 1934-1935 Prof. Vening Meinesz was onboard the Dutch submarine K-XVIII doing his historic pendulum gravity measurements with his "Gouden Kalf" instrument. Although there were some technical problems with the submarine in the Indian Ocean, he was able to perform 22 measurements from Mauritius to Fremantle. These measurements showed that near the coast of Western Australia gravity became weaker, indicating regional mass deficiencies due to either a deeper ocean floor or exceptionally low density of the solid Earth.

SEA LEVEL AND GRAVITY

The sea level surface at rest - so without such disturbing effects like tides, waves and ocean currents, folds itself perpendicular to the local gravity vector. If it would not be situated perpendicular to the local gravity vector, then there would be a net force in the horizontal direction, and the sea water would flow accordingly. The form of the sea level at rest, which is thus a gravitational equipotential surface of the Earth, is generally known as the geoid. Crudely stated, there are thus two ways to determine the sea level at rest, or geoid: by measuring its position with respect to the centre of mass of the Earth or by determining the gravity vector. The first option was impossible, even unthinkable, in the 1930's when artificial satellites and their applications like GPS with millimetre to decimetre accuracy belonged to the realm of science fiction and fantasy.

In practice, sea level is of course never at rest. And this has consequences for deriving the geoid from both gravity and positioning measurements. In fact, separating the steady-state geoid component from the dynamic components is one of the main objectives of the GOCE (Gravity and STEADY STATE Ocean Circulation Explorer) mission. GPS measurements of the sea level height over the Indian Ocean onboard a clipper, with its sea-sickness inducing movements, will always measure the sum of the steady-state (geoid) component and time-varying dynamic effects (waves, tides, ocean currents). In most circumstances the time-varying dynamic effects will be on the order of a few meters maximally and this should be compared to the several tens of meters that the geoid varies over the Indian Ocean. It is ultimately this order of magnitude difference that makes it useful topography on which to do the GPS-measurements for the purpose of showing the valleys and hills in the Indian Ocean surface.

SEA LEVEL CHANGE DUE TO ICE MASS CHANGES

The valleys and hills in the ocean sea surface topography (of up to 100m) have been formed due to tectonic processes over tens of millions of years. On shorter timescales, even down to human timescales, there are also considerable mass redistributions due to hydrological changes and continental ice mass variations. That gravity changes associated with ice mass changes over Greenland, Antarctica and mountain glaciers do affect the distribution of melt water over the world's oceans is an important issue. Due to the accompanying gravity changes, sea level will actually drop within about 2,000km around a melting continental ice sheet

Figure 2. From left to right: Geert-Jan Brummer (NIOZ – Texel), Lex Runderkamp (film director, VPRO & NOS), Henk Brinkhuis (Fac. Science, UU) and Bert Vermeersen discussing a next film set in the middle of the Indian Ocean

Figure 3. Position of the GPS antenna on the boatdeck

and will rise slightly for distances further away than about 7,000km. Thus, sea level change due to continental ice mass melt is never uniform, even not up to first order. How to explain this in a time slot of a few minutes in the tv-programme was one of the many discussions with the film crew onboard the Clipper (Figure 2).

GPS/GLONASS MEASUREMENTS

For the experiment, the Clipper Stad Amsterdam carried a high-precision geodetic GPS receiver which has been supplied by Fugro, Leidschendam. This receiver should be able to measure the sea-level height with an accuracy of about ten cm. The receiver is able to provide this accuracy by continuously tracking the US Global Positioning Satellites (GPS) and their Russian counterpart GLONASS. The receiver also received corrections to the GPS and GLONASS satellites from a geostationary satellite over the Indian Ocean in order to correct the measurements and make the high accuracy of the positions possible. These corrections are computed by Fugro from a global network of tracking stations and then sent to several geostationary satellites, from where they are broadcasted to the users with specially equipped receivers.

The GPS receiver on board the Clipper Stad Amsterdam provides two services: XP with GPS only, and G2 with GPS and GLONASS. The receiver is dual frequency L1/L2 GPS and GLONASS, capable of tracking the encrypted P-code on the second GPS frequency. The dual frequency capability is essential to eliminate signal delays caused by the Earth's ionosphere. Furthermore the receiver can correct for satellite orbit and clock errors through correction messages from a geostationary satellite. These corrections are computed by Fugro from a global network of tracking stations. Finally, by using very precise carrier phase measurements of the range to the satellites the receiver is able to compute the position with an accuracy of 10 cm.

The accuracy has been confirmed by tests on the ground before shipping the receiver to the Clipper Stad Amsterdam. The receiver was run for a 24 hour period on a stationary point. The standard deviation in latitude and longitude was five cm, the standard deviation in height ten cm. The accuracy for the XP and G2 service were very similar, although the G2 service gave slightly smaller standard deviations in height (nine cm). The main advantage of the G2 service, which includes GLONASS, is that it should be more robust due to the additional satellites. Over the 24 hour period we were able to observe 10-15 GPS+GLONASS satellites, compared to 8-10 GPS satellites.

The GPS receiver and antenna were installed on monday March 15, when the Clipper Stad Amsterdam was moored in Fremantle, Perth, Western Australia (Figure 1). The location for the antenna that was assigned to us was the railing on the boatdeck (Figure 3). This location turned out to be far from ideal: to port and starboard the view was obstructed by the ship's rescue vessels, and to the front and aft by the ships foremast and mainmast. However, we were given no choice, it was this location, or nothing else. The poor location of the antenna resulted in two main problems for tracking the GPS and GLONASS satellites: (i) only a very low number of satellites are being tracked, and (ii) for the satellites that are being tracked there are many interruptions due objects, such as the sloops, moving in and out of the signal path due to the rolling and pitching of the ship. As a result the position solution often fails due to lack of satellites or satellites moving in and out the solution. Also, after acquiring a sufficient number of satellites, it takes at least ten minutes for the position solution to converge and during which time no interruptions are allowed.

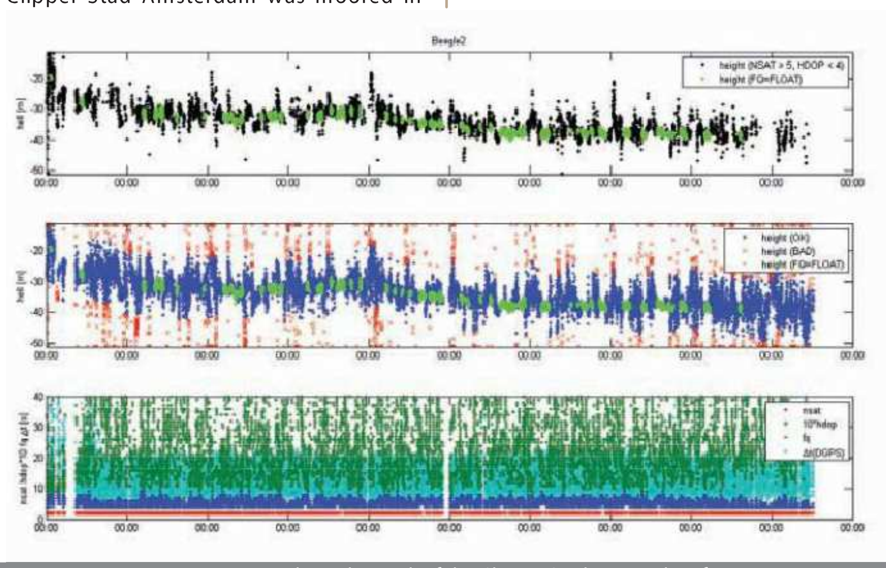

Figure 4. Position computations along the track of the Clipper Stad Amsterdam from May 16-25

FIRST RESULTS

Figure 4 shows some of the results of the position computations. The green points are position solutions which have ten cm accuracy. Cleary only a small fraction of the time, the receiver was able to compute an acceptable position solution. Obviously, the number of satellites that were tracked has been much lower than would have been visible with a clear view to the sky. However, the main source of problems with the position solutions has been the rolling and pitching of the ship resulting in frequent interruptions of the carrier phase tracking and frequent re-initialisations of the computations. Also, to our surprise, the combined GPS and GLONASS tracking (G2 solution) turned out to be worse than the GPS only solutions.

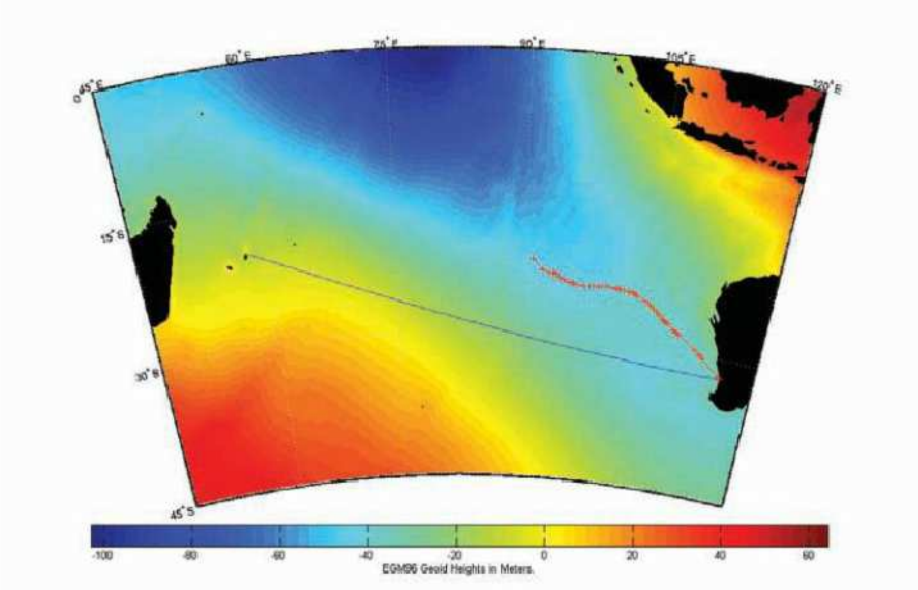

Figure 5. Track of the Clipper Stad Amsterdam from May 16-25 and EGM96 geoid height in the Indian Ocean

The track of the Clipper Stad Amsterdam from 16-25 May is shown in Figure 5. The figure shows the EGM96 geoid height in the Indian Ocean. The track of the Clipper Stad Amsterdam with successful position solutions is shown in red. The positions where the Clipper Stad Amsterdam has taken GPS height measurements are indicated by crosses. The great-circle route between Perth and Mauritius is shown as well. Clearly, the Clipper has taken a more northerly route in order to pick up the favourable trade winds. The track stops on the 25th of May due to a receiver malfunction. The cause of this failure is unknown. Because the Internet connection to the Stad Amsterdam was lost on the 18th of May, the receiver malfunction could not be repaired until after Mauritius.

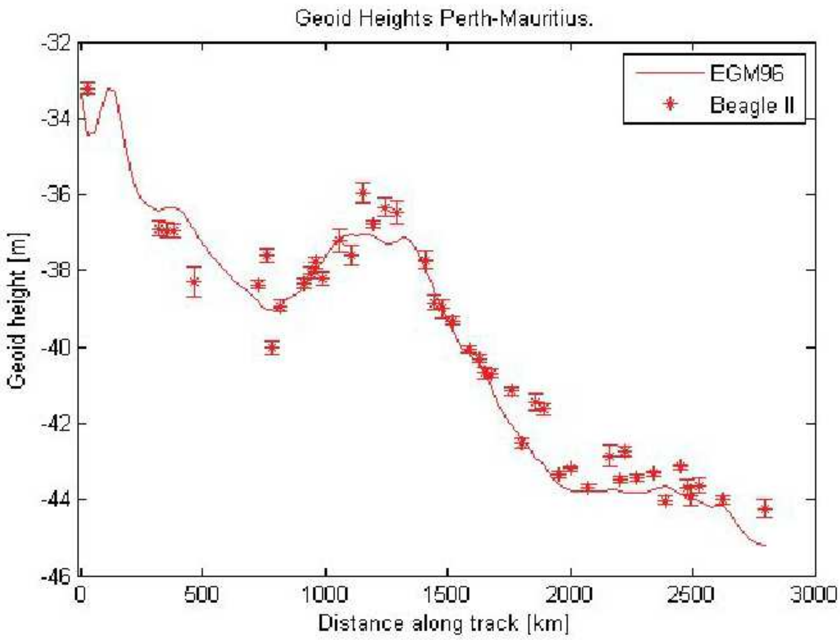

Figure 6. Geoid height including error bars as obtained from the GPS measurements onboard the Clipper Stad Amsterdam compared with the EGM96 model geoid

Figure 6 shows the geoid height as obtained from the GPS measurements on board the Clipper Stad Amsterdam with error bars, and compares these to the EGM96 model geoid height along the track of the previous figure. The measurements are in reasonable agreement, but there are also some differences. These differences can be explained as follows:

(1) Errors in the GPS measurements and motion of the ship. These are indicated by the error bars in the plot. Certainly the GPS measurement errors are a little larger than we would have liked because of the tracking problems, but the motion of the ship is causing the largest uncertainty here. In order to reduce this error we average GPS measurements over a period of about one hour. We did not yet correct for the pitch and roll. Although we have pitch and roll measurements, and could make such a correction, we have not done so yet. However, this is a relatively minor effect compared to the actual motion of the ship.

(2) Error in the model geoid height. The EGM96 is far from perfect and is just a simple geoid model. This is just a first - quick - comparison. There are other, much better and more recent, geoid models from recent and on-going satellite missions. We will include these in later comparisons. The error in the model geoid height is the main cause for the differences.

(3) Ocean tides and currents. We haven't corrected for these. On the contrary, these should have become "visible" as periodical effects for the ocean tides and lumps for the currents only if we would have had sufficient and almost continuous GPS tracking. It is in this area that the poor performance of the GPS hurts us most.

If the GPS would have performed better we would have had a continuous line with measured geoid and dynamic ocean heights instead of the few individual points we have now. Post-processing of the data could maybe help. The raw measurements are stored and better results could be obtained from post-processing as compared to the real-time processing on board. However, we don't expect wonders from this, as this will not solve the tracking problems.

At the moment we write this the measurements are still continued on the track from Mauritius to Cape Town, where the VPRO will disembark all apparatus and instruments of this exciting Beagle II – In Darwin's Footsteps expedition. We hope that the receiver will remain functional until then.

References

VPRO's Beagle II website:
http://beagle.vpro.nl

TU Delft's Beagle II website:
http://www.tudelft.nl/beagle