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CHICAGO
Chilean AeroGeophysical Observations
Survey Report

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Summary: This report describes the set-up, logistics and results of the CHICAGO (Chilean Coastal AeroGeophysical Observations) survey (Figure 0.1). It gives a short overview about the scientific intentions, detailed documentation of all technical aspects starting from the survey equipment via the aircraft installation to the GPS stations set-up and the experiences in flight. All processing results for the individual profiles are discussed in detail. Finally, the data is compared and combined with available recent marine gravity data and altimetry derived solutions.

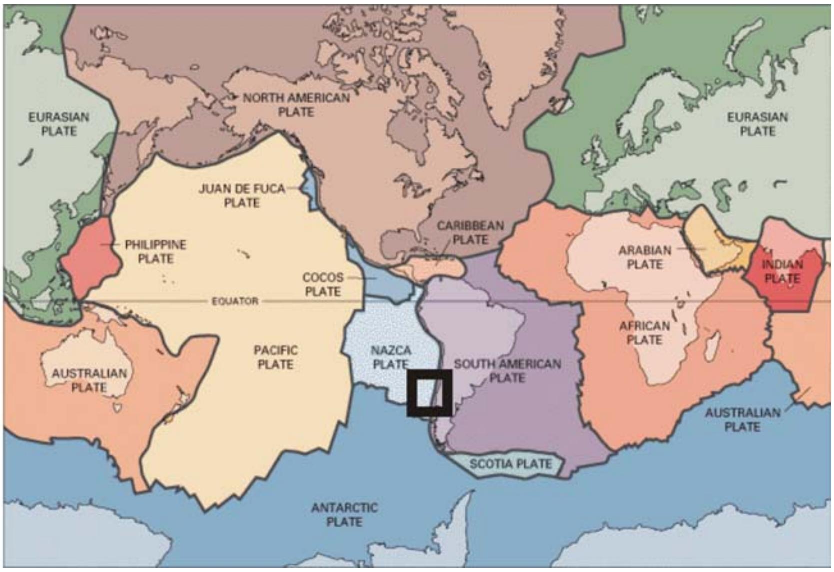

Figure 0.1: The fragmented earth and it's plates. The thick frame indicates the CHICAGO investigation area.

Contents

1 Introduction

Figure 1.1: View from aircraft to volcanoes in southern Chile.

Chile is one of the rare countries in the world that due to it's geographical position and longitudinal extension is nearly completely formed by a subduction zone (Figure 1.1 and 1.2a). The slightly oblique collision (~66mm/a and ~77°) [Angermann et al., 1999] of the eastern Pacific seafloor and the South American sub-continent and the subsequent dip of the easternmost part of the Pacific, the Nazca Plate (Figure 1.2b), under the South American sub-continent is physically accountable for the formation of one the largest mountain chains on earth, the Andes.

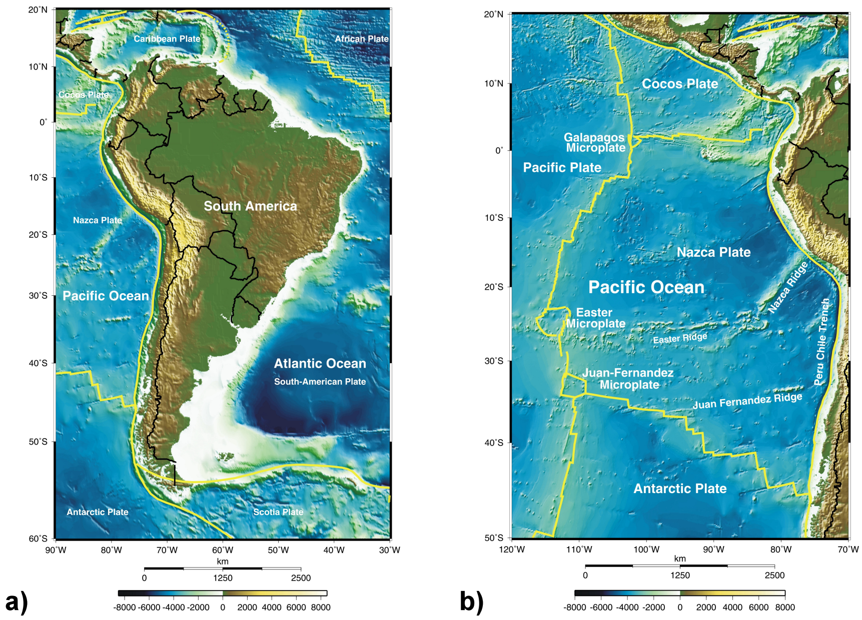

Figure 1.2: a) left: The South American sub-continent and it's surrounding plates. The Chilean coastline (~18° S to ~56° S) inherits the largest part of the Nazca plate – South America collision zone. **b)** right: The Nazca plate and its main structures.

The Andean mountain belt dominates much more than just the northern part of Chile. A cut through the oceanic and continental topography from west to east starts with the oceanic plate and its texture. A deep longitudinal abyss (Figure 1.2b and 1.3), the Peru-Chile trench, develops along the western coastline. On its western flank, the oceanic plate bulges up before it slides down steeply towards the east. In the central part of the Chilean subduction zone east to the coastline the coastal cordillera is formed, further towards the west a north-south trending valley lies in front of a volcano chain followed be the main cordillera (Figures 1.3, 1.4b and 1.5).

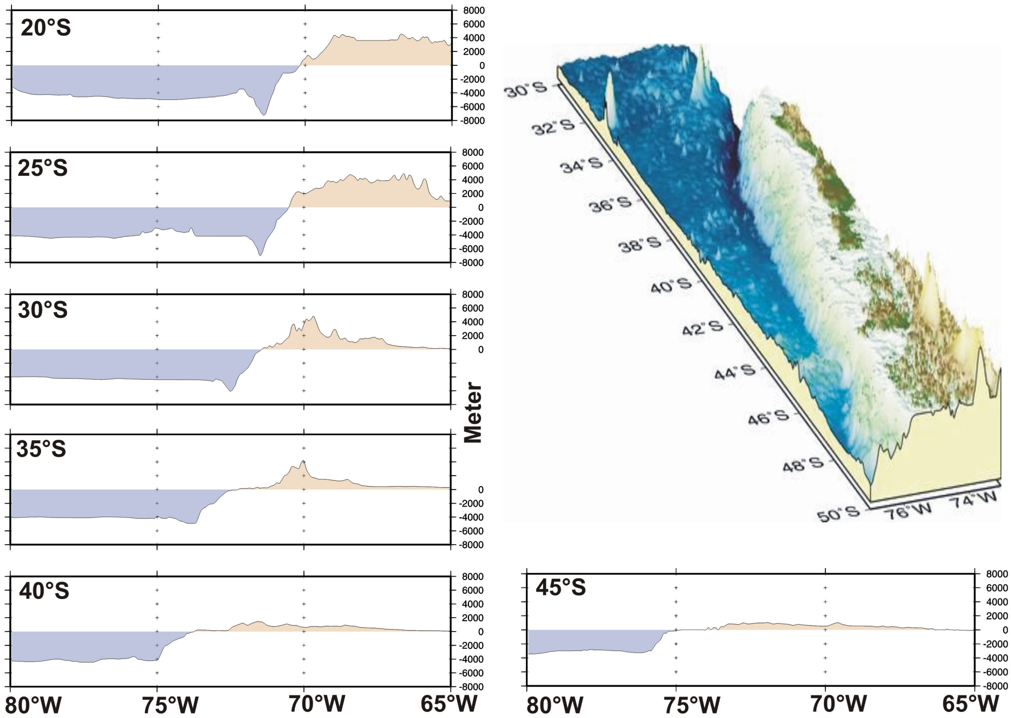

Figure 1.3: Sequence of six latitudinal bathymetry / topography profiles running from west to east at latitudes from 20°S to 45°S. It is clearly visible that the depth and signature of the trench diminishes towards the south whilst the mountain belt decreases in height and extent. The 3-dimensional picture of the trench from 30°S down to 50°S shows as well how the trench flattens towards the triple junction at about 47°S. The topographic and bathymetric data was extracted from ETOPO'2.

The trench system stretches over about 4000 km from Columbia and Peru down to the southern part of Chile. Between 5°S and 39°S the trench is a steep graben with strong contours. It defines a sharp division between oceanic and continental regimes. Around 39°S it's shape looses the sharp outline and it significantly flattens towards the south (Figure 1.3). At about 39°S the Valdivia Fracture Zone runs across the Nazca plate roughly west to east (Figure 1.4a and b, Figure 1.5). The fracture zone divides an older, colder and more rigid oceanic plate in the north (30°S: ~40 Ma) from a significantly younger, hotter and less rigid plate in the south (38°S: ~35 Ma, 40°S: ~0 Ma) [Herron, 1981]. Parallel to this the high mountaintops and plateaus in the north (15°S – 30°S: ~6000 m) decrease to low mountains and hills towards the south (33°S – 34°S: ~3000 m) (Figure 1.3). The same accounts for the coastal cordillera. The coastal mountain chain drops from ~ 1800 m to ~800 m between 33°S and 39°S. The strongest changes in the longitudinal topography and bathymetry are found around 39°S. Exactly here we also find a significant break in the gravimetric pattern as we will see later in this report. The geology of the continental part around 39°S is given in Figure 1.5. Here, beyond the topographic expression, the main fault zones are mapped. In this area they mainly trend NE-SW-wards (Bio-Bio-, Gastre-Fault Zone) running across N-S trending fault zones at the western flank of the main cordillera [Bohm et al, 2002]. Already these surface-based observations lead to the questions why the northern part and the southern part of the Chilean subduction zone behave so differently and if changes in subduction and mountain building processes can be accounted for. For these reasons the ocean-continent boundary along 39°S was defined as the center point of our airborne survey (Figure 1.6a). The survey was designed to be conducted from an airborne platform in order to map the ocean-continent boundary without gaps in a short amount of time. The survey was split into two campaigns. The first campaign was set-up to map the transition zone between 37°S and 39°S, the second between 39°S and 41°S. The northern part was flown first for several reasons. Firstly, it covers and complements part of the RV Sonne cruise in 2001 (Figure 1.6b) to get an idea about system performance by comparing the surveys. Secondly, the weather in the northern part is considerably more stable over an extended summer period. Thirdly, this was the first aerogravity campaign in Chile and the logistic environment was easier to employ in the northern part.

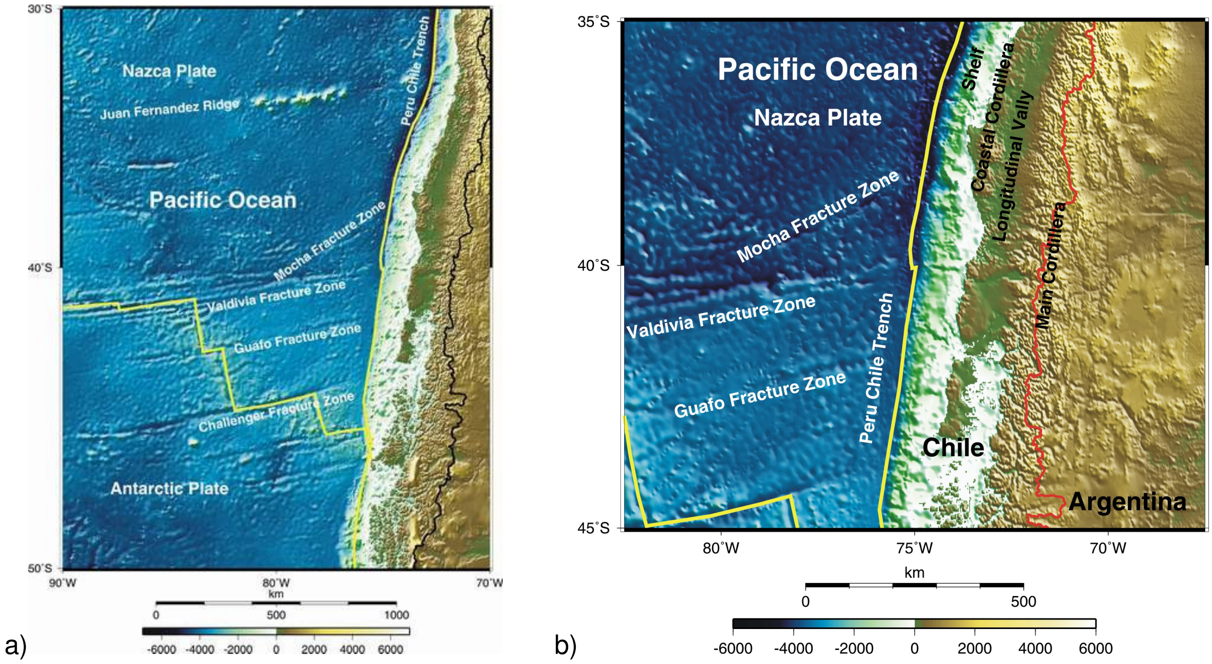

Figure 1.4: a) right: The southern part of the Nazca plate and the triple junction. **b)** left: Main bathymetric and topographic features of the investigation area.

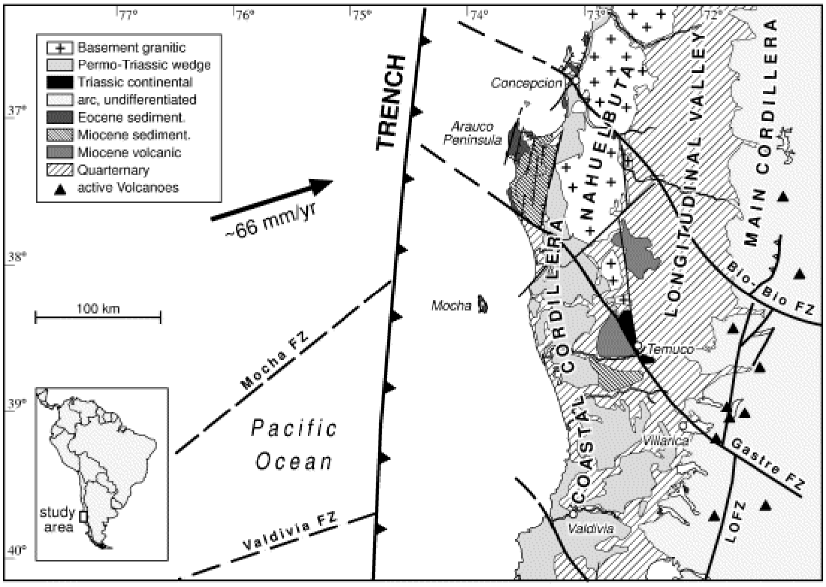

Figure 1.5: Taken from [Bohm et. al, 2002]: geological map of the Chilean part of the investigation area showing the major tectonic units and fault zones.

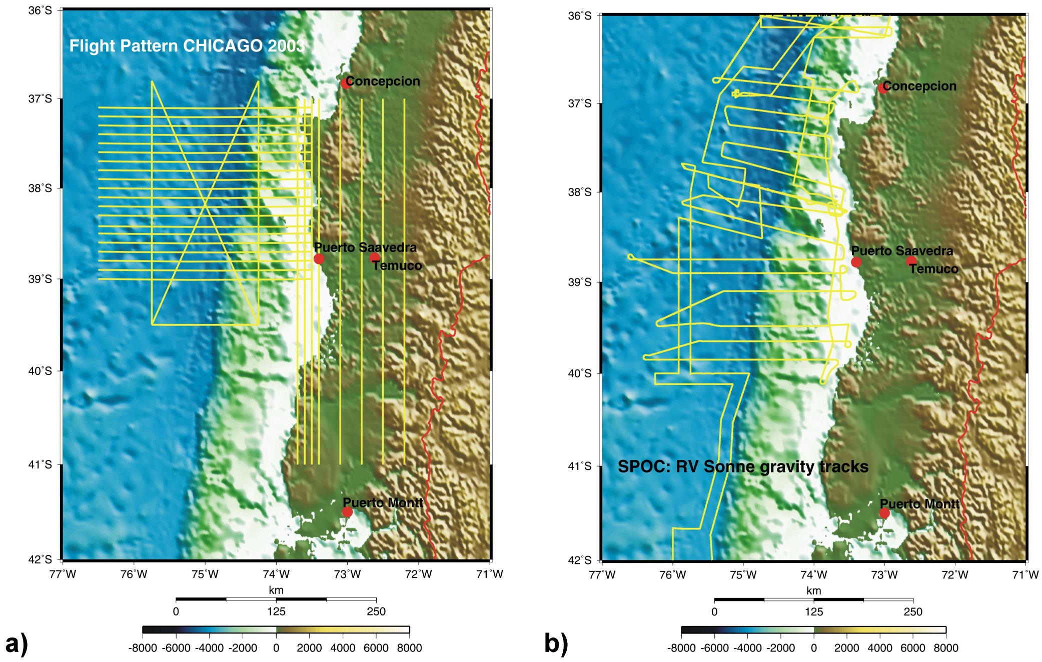

Figure 1.6: **a**) right: Flight lines of the CHICAGO aerogravimetric survey. **b)** left: Marine track lines from the SPOC survey with RV Sonne.

A second scientific aim was to try to map asperities by their gravimetric expressions. Asperities are patches of oceanic or continental crust that have a stronger resistance to deformation than their environment. If asperities break, up to mega-thrust earthquakes are triggered (Figure 1.7). Therefore, asperity mapping is one of the most crucial tasks in subduction zone areas because here, 90% of the large-scale earthquakes occur.

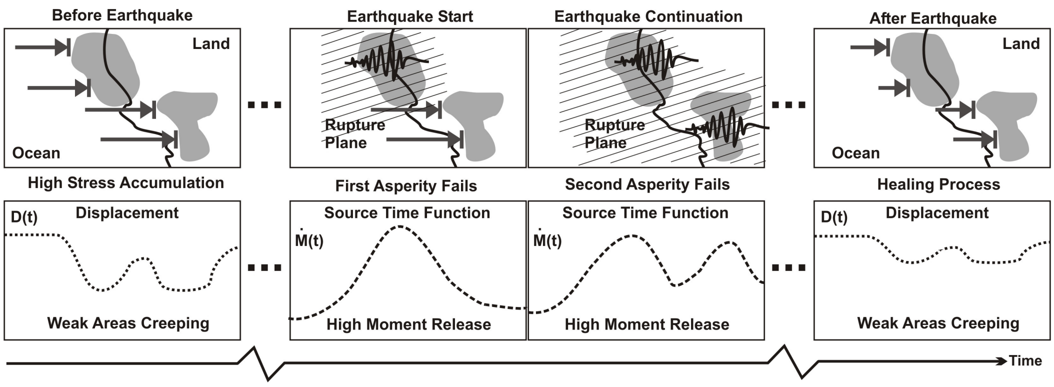

Figure 1.7: Asperity model: asperity patches accumulate stress until they break and trigger earthquakes.

In order to fulfill these tasks, support and co-operation was needed from German and Chilean partners. The SFB267 supported the project financially and in terms of personnel. On the Chilean side the Instituto Geografico Militar (IGM) in Santiago and the Servicio Aerofotogramétrico (SAF) of the Chilean Air Force were indispensable partners. An aircraft of the SAF was used to employ the aerogravimetric survey system of the GFZ. Personnel from both institutes, IGM and SAF, were essential to perform the survey. Details of the co-operation and technical issues are given in later chapters of this report.

2 Logistic set-up and co-operations

In order to prepare the aerogravimetric survey help and assistance in Chile was needed. Therefore, a total of four institutions were involved in the survey (Figure 2.1). Within Germany, the SFB267 “Deformation Processes in the Andes” sponsored the survey. Andres Tassara, an SFB-member from the Free University of Berlin (FUB), was sent with the CHICAGO team as a translator and responsible scientist for ground based gravity measurements. The GFZ already had good connections to the Instituto Geográfico Militar (IGM) in Chile due to the common static GPS station network and several common GPS campaigns. The head of IGM is at present General Pablo Gran Lopez. Our main partner at IGM was Teniente Coronel Rodrigo Maturana Nadal of the Departmento Geodésico. He arranged the contact to the Servicio Aerofotogramétrico (SAF) of the Chilean Air Force. SAF was able to supply a Twin Otter aircraft that so far was only used for aero-photogrammetric surveys. At SAF, Coronel de Aviacion Christian Gomez Meneses, Jefe del Servicio Aerofotogramétrico, was our official contact and responsible partner. IGM was in charge of all customs activities for import and export of all scientific goods as well as for transport and accommodation in Santiago (Figure 2.2). SAF was in charge of all aircraft installations and flight operations (Figure 2.3). About one ton of scientific instruments were sent to Santiago de Chile. The instrumentation covered all ground based stations, all flight instrumentation and installation material, all necessary tools and equipment for the technical installations and computers, hardware and software for data flight planning, data storage, quality check and first compilations (Figs 2.4 and 2.5). The GPS-station at TIGO (Transportable Integrative Geodetic Observatory) run by the Bundesamt für Kartographie und Geodäsie (BKG) / Fundamentalstation Wettzell was used as a fixed control station for the transportable GPS stations used in CHICAGO.

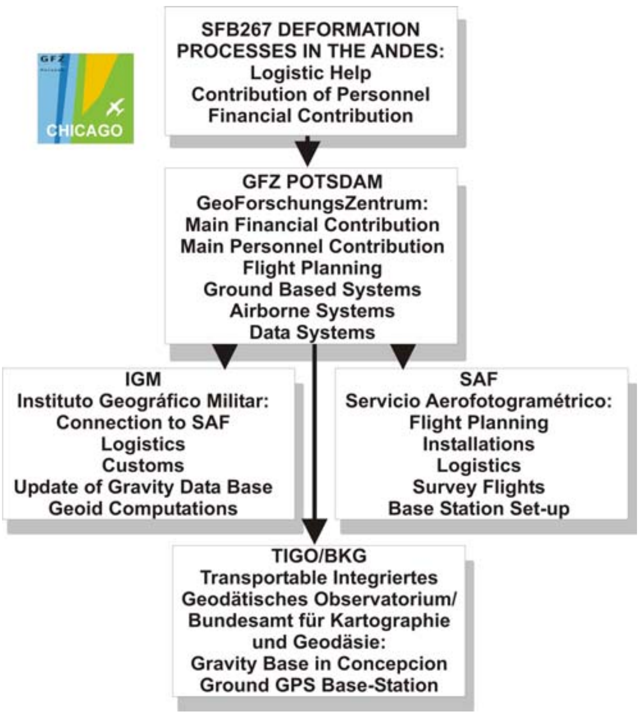

Figure 2.1: Institutions involved in the CHICAGO (Chilean Coastal AeroGeophysical Observations) survey. Project leader was Dr. Uwe Meyer, GeoForschungsZentrum, Telegrafenberg A17, 14473 Potsdam. The e-mail address is umeyer@gfz-potsdam.de. The GFZ team was formed by Uwe Meyer, scientist, Hartmut Pflug, engineer and Martin Krüger, mechanic.

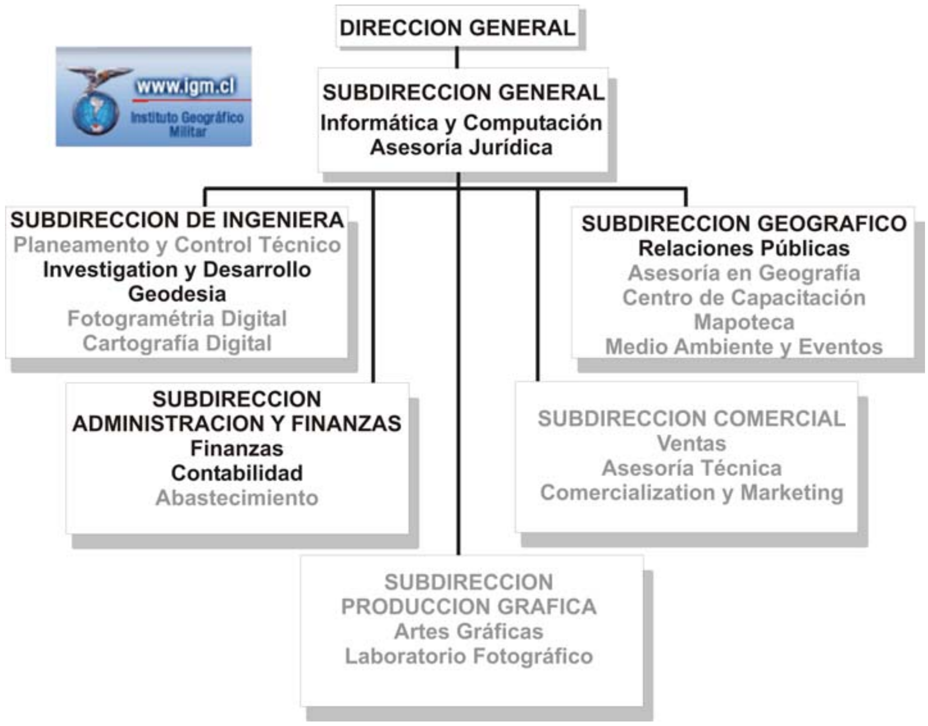

Figure 2.2: Internal structure of the Instituto Geográfico Militar (IGM) in Santiago de Chile. The departments that were involved in the CHICAGO survey are highlighted. Contact address at IGM is Jefe Departamento Geodésico Rodrigo Maturana Nadal, Instituto Geográfico Militar, Nueva Santa Isabel 1640, Santiago Centro, Chile. The e-mail address is rmaturana@igm.cl.

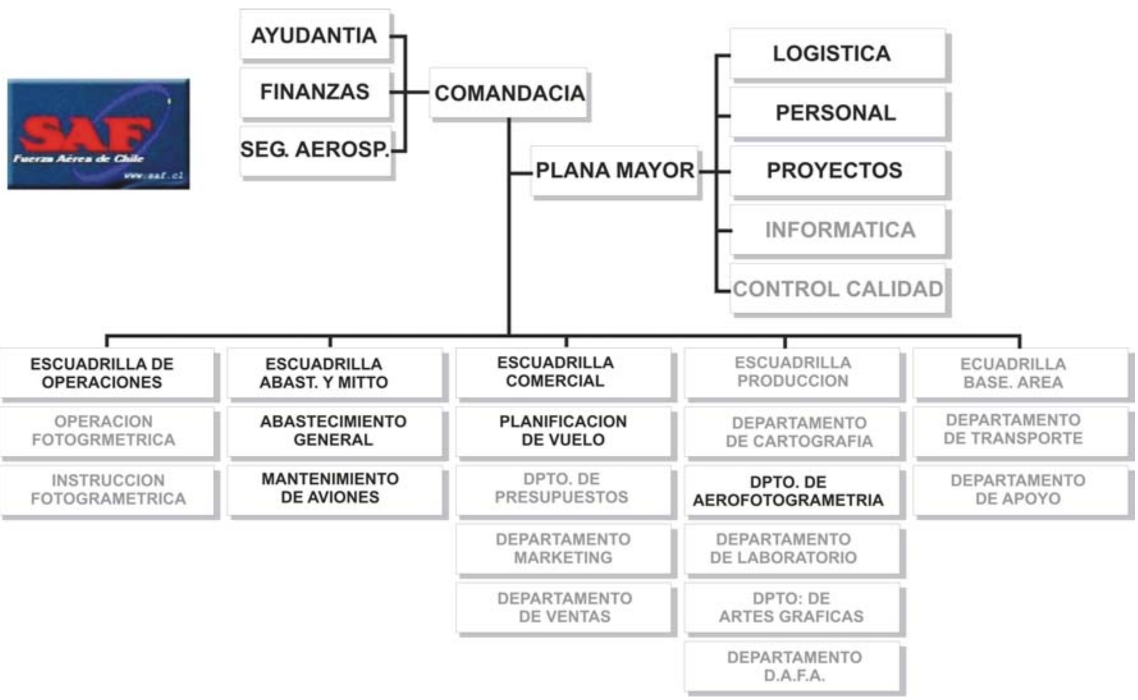

Figure 2.3: Internal structure of the Servicio Aerofotogrametrico (SAF) based in Santiago de Chile. The departments that were involved in the CHICAGO survey are highlighted. Contact address at SAF is Subgerente Comercial Edgardo Manriquez Contreras, Avenida Pedro Aguirre Cerda # 6100, Los Cerillos, Santiago. The e-mail address is emanriq@saf.cl.

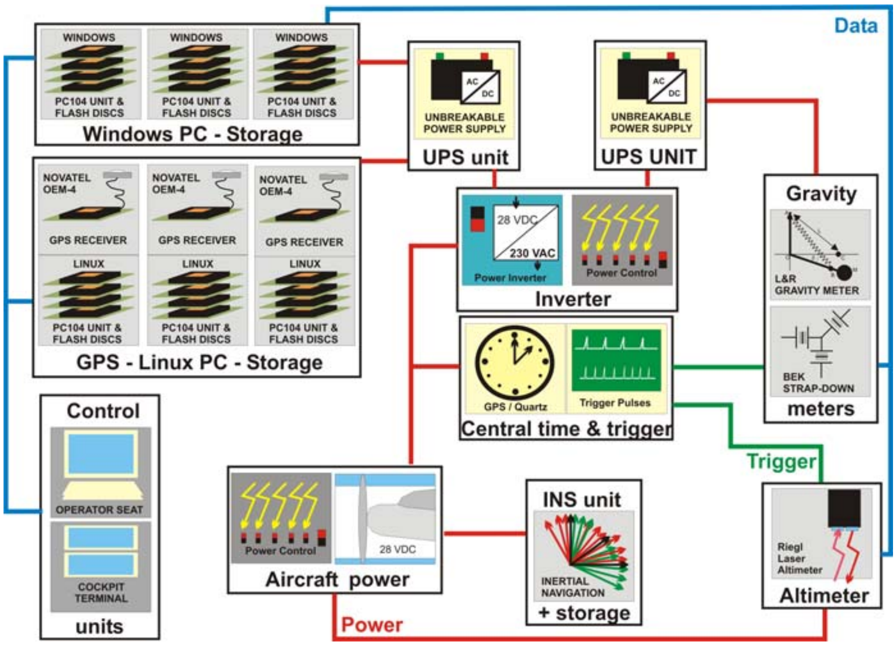

Figure 2.4: GFZ Potsdam airborne system components.

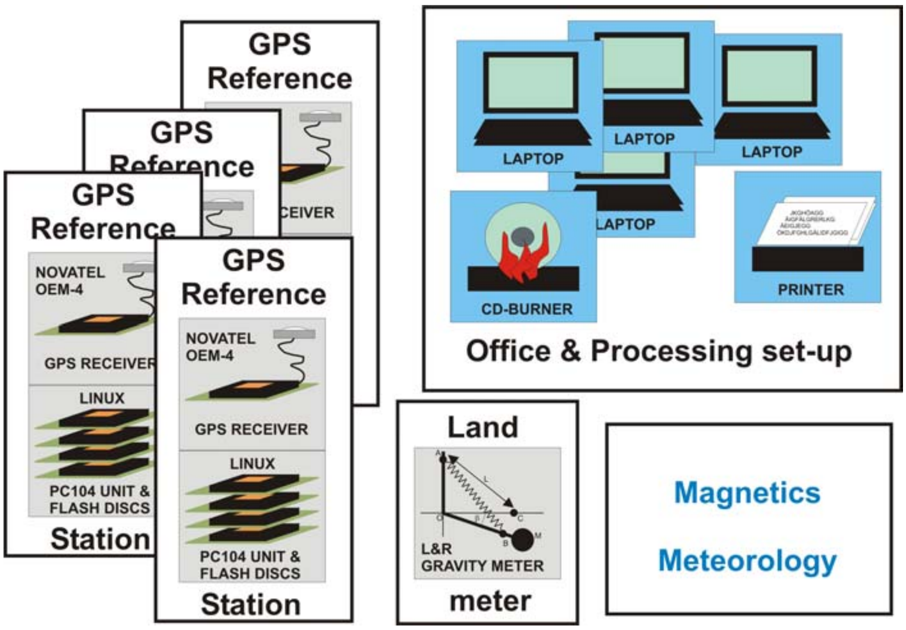

Figure 2.5: GFZ Potsdam ground system components.

All scientific equipment was sent from GFZ Potsdam via IGM in Santiago to SAF at the Base Area in Los Cerillos. There, all technical installation on the Twin Otter aircraft was worked on. Most of the technical installation documentation was prepared beforehand. Most of the logistics involving the aircraft and ground station handling was organized from SAF head quarters. Parallel to the installation work some last changes on the contracts between GFZ, IGM and SAF were mutually worked out. All installation test work was done at and from Los Cerillos airport in Santiago de Chile. After the installation period was over, the aircraft and survey crew was transferred to Temuco. SAF is in control about the military part of the airport at Temuco. Located at the center latitude of the survey area, Temuco was a perfect logistic base to carry out the survey. At the military head quarters building on the site of the airport, our group was allowed to use a comfortable, well equipped office. All preparation and survey work was escorted by two attaché officers, namely Major Donosso and Major Zamora. Thanks to their help, we were able to communicate without trouble and to organize even last minute logistics without problems. Between SAF offices and the apron we were able to install our main GPS ground based station. A second station was set up on public school in Puerto Saavedra and on the military part of the airport of Puerto Montt (Figure 2.6). The temporary GPS network was linked to the TIGO GPS base station. Details of the GPS station set-up are given in a subsequent chapter.

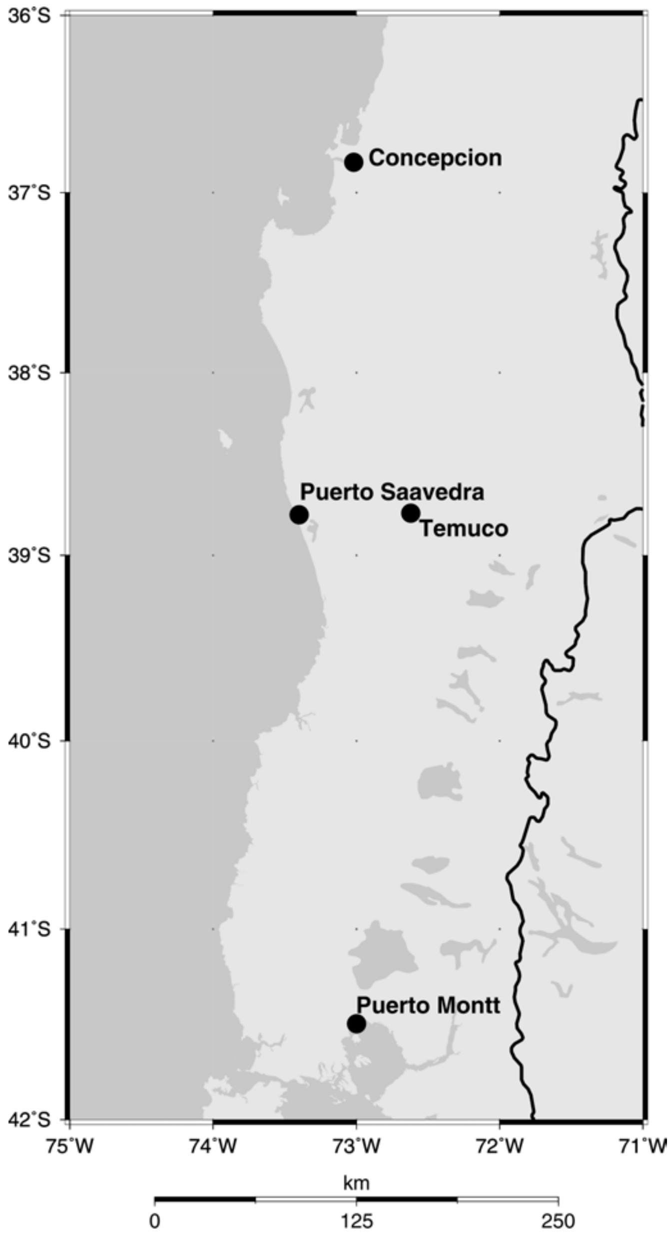

Figure 2.6: Location of the survey and GPS base in Temuco and the GPS bases in Concepcion, Puerto Saavedra and Puerto Montt.

3 The aircraft and crew

3.1 The survey aircraft

The aircraft used for the CHICAGO survey is a de Havilland DHC-6 Twin Otter (Figure 3.1). This type of aircraft is used all over the world for aerogravimetric surveys (British Antarctic Survey, ETH Zurich & Swiss Air, Lamont Doherty Observatory & NSF, Iceland Air / KMS) because of its reliability and stable flight performance. Most of the Twin Otter aircraft still in service are more than 40 years old. The Twin Otter of the SAF had a service lifetime of about 36 years. SAF had used it so far only for airborne photogrammetric surveys. For the GFZ, it was the first installation of its aerogravimetric survey system in a DHC-6. The scientific instruments were installed without any major problems with the help a very capable service and engineering team from SAF. The only major disadvantage was the lack of an autopilot. The installation of an autopilot for the CHICAGO survey was discussed but then omitted because of its high costs (the total survey cost nearly equaled the installation costs for an auto-pilot system, not regarding time for testing and certification).

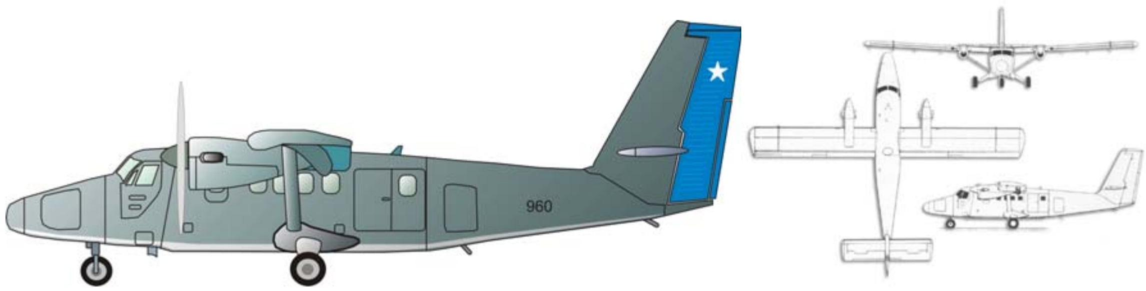

Figure 3.1: Drawings of the de Havilland DHC-6 Twin Otter aircraft of the Servicio Aerofotogramétrico (SAF) in Santiago.

General technical details of the aircraft are given in Table 3.1.

Type:	twin piston engine aircraft
Crew:	2 pilots plus max. 6 scientists
Ceiling:	12500 ft (25000 ft with oxygen)
Speed:	80 to 160 kts
Weight:	8100 lbs (empty), 4400 lbs (load)
Fuel:	2500 lbs (plus 1000 lbs auxiliary)
Fuel flow:	580 lbs/h (average)
Wingspan:	65 ft
Length:	52 ft (total external)
Fuselage:	9 ft (external height)
Cabin length:	18 ft (internal)
Cabin height:	9 inches (internal)
Cabin width:	52 inches (internal)
Cabin volume:	385 cu ft

Table 3.1: Technical details of the de Havilland DHC-6 Twin Otter

The aircraft showed no major technical failures and therefore could be used for all survey flights without delays. For the last flights covering long distances, an extra fuel tank was installed in the cabin.

3.2 The aircraft crew

Figure 3.2: Aircraft team including pilots, aircraft technicians and science crew.

The aircraft crew for the CHICAGO survey consisted of aircraft mechanics and electricians, pilots and the GFZ team. The aircraft technicians were extremely helpful during the installation and later survey period. The hangar and workshop of the SAF at Temuco was well equipped for our purposes, which ensured a relatively quick and safe installation within less than one week, including first ground system tests. In case of an aircraft failure a second Twin Otter was ordered to stand-by. In the preparation phase, intense discussions with the pilots took place in order to manage the flight preparations on ground and on the air, discuss emergency procedures for system and for aircraft failure as well as meteorological and flight conditions. For most of the planning and flight preparation the FliteStar program purchased by GFZ was used. Two laptops were hooked on the Internet to download the weather forecasts and other necessary data.

The CHICAGO team immensely relied on the logistics of SAF, including a large office room at SAF headquarters at Temuco airport. In order to prepare the survey logistics and requirements of all other sorts, two attaché officers were with the GFZ team. Their help was happily accepted. For the onshore flights we were allowed to use the military airport of Puerto Montt to set-up a GPS reference station. At Temuco such a station was running more or less permanently.

4 Aircraft installations

All documentation for the mechanic and electric installation was documented before the survey. This work guaranteed a quick set-up of the instruments on board of the aircraft. The interface between aircraft and scientific instrumentation were mounting plates on the mechanic side and connection to primary ground and aircraft power on the electric side. Some more work was required for the installation of the laser altimeter. At this point, the observation window for the photogrammetric camera system had to be modified. For the installation of the wing tip GPS antenna large parts of the one of the aircraft wings had to be opened to install the antenna cable. This cable was left in place after the CHICAGO survey for future use. Figure 4.1 shows the work on the aircraft and part of the installation. Figure 4.2 shows a schematic overview of the aircraft installation.

Figure 4.1: left: installation work; right: part of the installed equipment in the aircraft: at front SAGS 2.2 sensor, behind it LaCoste & Romberg gravity meter, in the rear the instrument rack.

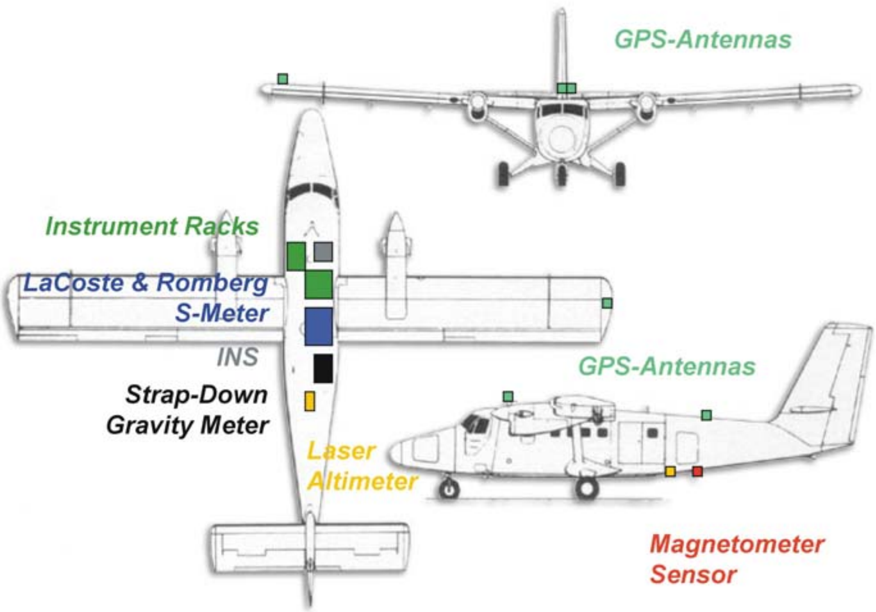

Figure 4.2: Mechanic installation of the ANGEL system in the SAF Twin Otter

The instruments had to be installed in way that the weight and balance of the aircraft was still in the allowed frame. In order to ensure this weight and balance check were made at GFZ beforehand using the FliteStar program and a suitable model of the Twin Otter aircraft. An overview about the installed instruments and their weights are given in Table 4.1. The electric power consumption of the main instruments is given in Table 4.2. A magnetometer system was installed but could not be used due to strong aircraft field interferences.

Instrument *Instrument*	Gewicht *Weight* [kg]
Grundplatte Instrumentengestell / Bottom Plate Intrument Rack	?
Instrumentengestell ohne Bestückung / *Instrument Rack without Equipment*	12.0
IGI INS-Console / IGI INS-Console	7.0
LaCosta Romberg PC / LaCosta Romberg PC	20.5
GPS PC Console 19"-Einschub / GPS PC Console 19" Unit	15.0
Windows PC Console 19"-Einschub / Windows PC Console 19" Unit	8.0
Meinberg Trigger 19"-Einschub / Meinberg Trigger 19" Unit	10.5
PC- Umschalter / PC-Switch	1.0
Stromverteilung Schaltkasten / *Power Distribution Switch Board*	9.0
Grundplatte Operatorgestell / Bottom Plate Operator Rack	?
Operatorgestell ohne Bestückung / Operator Rack without Equitment	4.0
Inverter / Inverter	8.5
Bildschirm / Monitor	1.0
Tastatur und Maus / keyboard and mousepanel	0.5
Grundplatte Laser-Altimeter / Bottom Plate Laser-Altimeter	?
Laser-Altimeter Sensor / Laser-Altimeter Sensor	2.0
Netzteil / Power Unit	2.0
Magnetotmeter – Console / Magnetometer – Console	5.0
Magnetotmeter – Sensor / Magnetometer - Sensor	1.5
Grundplatte IGI System / Bottom Plate IGI System	?
IGI INS E-Box / *IGI INS E-Box*	8.0
IGI INS Sensor / IGI INS Sensor	2.0
Grundplatte SAGS 2.2 / Bottom Plate SAGS 2.2	
SAGS 2.2 Sensor + Plattform/ *SAGS-2.2 Sensor+ Rack*	52.0
Grundplatte Gravimeter / Bottom Plate Gravimeter	?
Netzteil UPS / Power Unit UPS	30.0
LaCosta Romberg Gravimeter / LaCost Romberg Gravimeter	50.0

Table 4.1: Installed instruments and weight.

Elektrischer Verbraucher **Electrical Unit**	**Leitstungsaufnahme** **Power Consumption**
Laseraltimeter Z-LAS-01	10 Watts @ 28 VDC
SAGS-2 Sensor Z-SAG-01 Meinberg Clock Z-MBC-01	70 Watts @ 28 VDC 10 Watts @ 220 VAC
GPS PC Z-GPS-PC-01 WIN PC Z-WIN-PC-01	150 Watts @ 220 VAC 150 Watts @ 220 VAC
Magnetometer Z-MAG-01	50 Watts @ 220 VAC
IGI-Console Z-IGI-01 IGI-IMU / Sensor Z-IGI-02 Ashtech GPS Rx Z-ASH-01	50 Watts @ 28 VDC 300 Watts @ 28 VDC 7.5 Watts @ 28 VDC
S124 Gravitymeter Z-LLC-01	300 Watts @ 220 VDC

Table 4.2: Main instruments and their power consumption.

5 Aircraft equipment

5.1 LaCoste & Romberg S124b gravity meter system

The LaCoste & Romberg air/sea gravity meter Model S124b (Figure 5.1) consists of a highly damped, spring type gravity sensor mounted on a gyro stabilized platform with associated electronics to obtain gravity readings. The original theory behind the LaCoste & Romberg Air/Sea gravity meter is given in LaCoste et al. [1967]. Technical details about the instrument are given in Tables 5.1 and 5.2.

Figure 5.2: LaCoste & Romberg S124b gravity meter in GFZ laboratory

The Model S sensor incorporates a hinged beam supported by a zero-length spring (a zero-length spring is a spring whose equilibrium length with a test mass attached is zero, see Figure 5.2). The damping of the large vertical accelerations due to the aircraft's motion is achieved through the use of internal air dampers. Nevertheless, the vertical accelerations of the aircraft makes it impossible to keep the beam constantly nulled. Therefore, it is necessary to read the gravity sensor when the beam is in motion. A mathematical analysis of the spring type gravity sensor shows that this is possible through the observations of: the beam position, the beam velocity and the beam acceleration at any given time. If the beam motion is highly damped, the beam acceleration term can be neglected. If the gravity sensor has a very high sensitivity over a high range, the beam position can be neglected as well. The LaCoste & Romberg S-meter fulfils both requirements. Accordingly, it can be read without nulling it via the measurement of the beam position parallel to the adjusted spring tension.

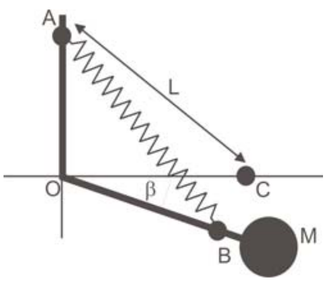

Figure 5.1: Simplified principle of a zero-length suspension system: The mass M is attached to the moveable beam OB that is free to rotate about O. The beam is supported by a zero-length spring attached at the points A and B. In practice, the beams total travel distance between top stop and bottom stop is about some mm in the Model S meter.

Utilizing the zero-length spring principle in a particular geometry results in a vertical suspension that can have infinite periods [LaCoste et al., 1988]. When the period is infinite and the torque exerted by the spring tension exactly balances the torque exerted by gravity, the beam will remain stationary at any position. When this position is achieved, the smallest change in gravity will cause the beam to rotate to one stop or the other. Thus, infinite period corresponds to infinite sensitivity [Valliant et al., 1992]. If the period is less than infinite and the beam is displaced from its equilibrium position, a restoring torque will return it back to the equilibrium position – this is the case for land gravity meters.

So finally, for the Model S meter the basic equation to gain the relative gravity at a given time and thus at a given location is:

dg = S x M = Spring Tension + k x Beam Velocity + Cross Coupling Errors.

Here, k is a constant depending on the adjustment of the physical damping which is mainly dependant on the quality of the air dampers implemented in the system (see Figure 5.3). M is the actual measurement in scale units; S is the scale factor to convert the readings into mGal. Of course in our case dg only represents a relative measurement meaning only the changes in the gravity field are detected.

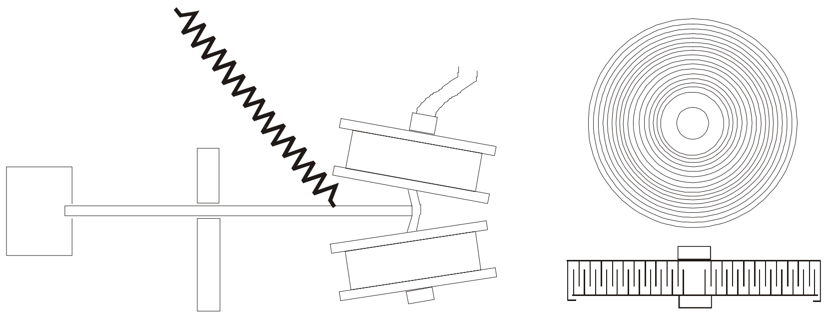

Figure 5.3: Schematic sketch on beam damping (right end of beam with hose for air pump) and box for capacitive beam position measurement (left end of beam) plus top and side cut view of an air damper.

For best performance and accuracy of the airborne gravity measurements it is mandatory to keep the platform that holds the gravity meter system as close to horizontal level as possible. For this task for each of the two horizontal axes an accelerometer and a gyro is implemented. The accelerometer itself is being manually controlled and leveled when the gravity meter is in an undisturbed environment. The accelerometer then is being nulled with the help of a precise water level on top of the platform. The output signal of the accelerometer is linear with the tilt angle of the platform and has a maximum range of about 16°. The accelerometer signal is sent to the gyro processor meaning the signal is appropriately shaped for gyro input. The gyro itself only measures the angular rates of the platform but has no information of its own about the spatial orientation. Therefore, the accelerometer input is needed. The combined signals are filtered and sent to the servomotor to correct actual deviations of the platform from the horizontal (see Figure 5.4). The reaction time of this negative feedback loop is close to immediate but it has a limited "memory" due to the gyro drift. The memory time used with the filter is about 5 minutes for airborne application and 11 minutes for ship operations. On the LaCoste & Romberg S124b platform optical gyros are used for attitude control. They do not need any heating as mechanic gyros and have excellent control about rapid angular changes.

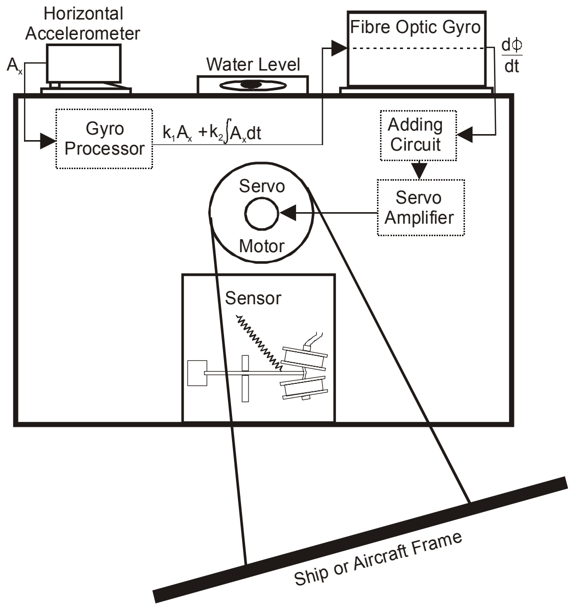

Figure 5.4: Schematic sketch of the platform horizontal leveling in one axis

Platform physical size:	55 cm (22”) W x 70 cm (27”) D x 64 cm (25”) H
Platform weight with sensor:	79 kg (175 lbs.)
Center of gravity height:	28 cm (15”)
Driver / Computer unit size:	46.5 cm (19”) W x 48 cm (18.9”) D x 27 cm (10.6”) H
Driver / Computer unit weight:	21 kg (46 lbs.)
Keyboard unit size:	46.5 cm (19 “) W x 44 cm (17.3”) D x 4.5 cm (2”) H
Keyboard unit weight:	7 kg (15.5 lbs.)
UPS physical size:	43.3 cm (17”) W x 41 cm (16”) D x 9 cm (4”) H
UPS weight:	19 kg (42 lbs.)
Operating temperature:	0°C to 40°C (32°F to 104° F)
Storage temperature:	-30°C to 50°C (-22° F to 122° F)
Power requirements:	300 Watts @ 115/230 VAC or ~ 1.5 A @ 230VAC

Table 5.1: Physical properties of the LaCoste & Romberg S124b gravity meter

Range:	12,000 mGal
Drift:	3.0 mGal per month or less
Temperature set point:	49° C
k-Factor (internally, static beam):	1.37
k-Factor (externally, dynamic beam):	39.0
Scale-factor (spring tension):	1.014
Stabilized platform specification	
Platform pitch (mechanical):	± 25 degrees
Platform roll (mechanical):	± 25 degrees
Platform pitch (accelerometer range):	± 16 degrees
Platform roll (accelerometer range):	± 16 degrees
Platform period:	4 minutes
Platform damping:	0.707 of critical period
Control systems specifications	
Recording rate:	1Hz plus 10Hz for beam positions (AIRSEA 3.1)
Serial output:	RS-232
Additional output:	3 analogue channels (±10V)
Gravity systems specification:	
Accuracy in laboratory:	50000 mGal horizontal acceleration (± 0.25 mGal) 100,000 mGal horizontal acceleration (± 0.50 mGal) 100,000 mGal vertical acceleration (± 0.25 mGal)

Table 5.1: Performance parameters of the LaCoste & Romberg S124b gravity meter

5.2 SAGS 2.2 strap-down gravity meter system

The strap-down system described in the following section is owned and developed by the Bayerische Akademie der Wissenschaften in München (BADW). Responsible for the design of the instrument and the research on this topic at the Bayerische Kommission für Internationale Erdmessung (BEK, within BADW) is Dr. Gerd Boedecker.

The strap-down concept offers some important advantages when compared to conventional airborne gravity meters as the LaCoste & Romberg S124b: a potentially higher spatial resolution, an improved and simplified handling, significantly less volume and weight plus the potential to gain gravity vector observations. Other strap-down system developers in the field of aerogravimetry use off-the-shelf inertial navigation systems. These systems suffer from the handicap that they are optimized only to get the navigation and attitude solution precisely but not gravity. They are mostly not temperature controlled, therefore then have high drift rates and generally allow only limited access to the signal processing. Thus, an independent solution from INS packages was strived for. Within SAGS-2.2 (Figure 5.5), Q-Flex accelerometers have been utilized. These sensors still have the best potential for gravity observations and are used as industry reference for acceleration measurements of all kinds. The integral Q-Flex electronics develops an acceleration-proportional output current providing both static and dynamic acceleration measurement. Through the use of a customer supplied output load resistor, appropriately scaled for the acceleration range of the application, the output current can be converted into a voltage. The QA-3000 includes a current-output and an internal temperature sensor. Through the use of a temperature-compensating algorithm bias, scale factor and axis misalignment performance is dramatically improved.

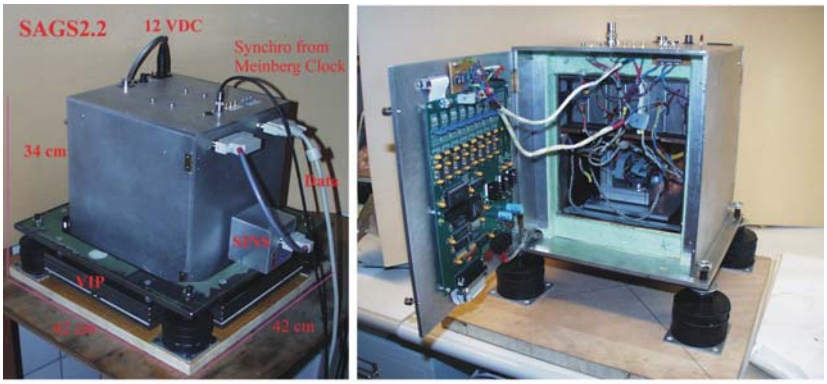

Figure 5.5: SAGS 2.2 in the laboratory of BADW/BEK.

To reduce temperature and electromagnetic noise effects on the Q-Flex sensors special shields were tested and implemented in the SAGS housing. Additionally, a vibration-damping platform to hold the housing was constructed. The SAGS control and data acquisition system was individually developed for this purpose running on a laptop using a MatLab environment.

In detail, SAGS-2.2 implements 3 Q-Flex® Quartz Accelerometer 3000 (QA-3000) within an airborne strap-down system to measure 3D accelerations resulting from gravity and kinematics (see Figure 5.6). Primary applications of QA-3000 include spacecraft navigation and control systems. The QA-3000 features an etched quartz flexure seismic system. The proof mass is etched from a single piece of quartz to form an outer, stationary mounting ring and an inner pendulous disk The disk is connected to the outer ring by two thin flexures or "hinges". These flexures tightly constrain the proof mass and allow rotation only about the hinge axis. The amorphous quartz makes an ideal material from which to form proof mass and flexures, which are essentially perfectly elastic. There is no energy lost in their bending. The dimensional stability of the material also guarantees unchanging proof mass parameters as size and mass. It provides excellent bias, scale factor, and axis alignment stability. The Q-Flex accelerometer combines advantages of fused quartz with solid-state servo electronics. Acceleration along the sensitive axis creates a force on the proof mass pendulum, displacing it slightly, causing a signal in a capacitive null detector. In response to this signal a servo circuit sends a current through coils attached to the proof mass. The current in these coils, moving through a permanent magnetic field mechanically restores the proof mass to the null or balanced position. The current required to re-balance the proof mass is proportional to the input acceleration. The basic formula for the accelerometer output as a function of the acceleration input is:

Output = Scale Factor x (Acceleration along input axis + Bias).

Please note that the scale factor and the bias depend also on temperature, axis misalignment and vibration.

The minimum configuration for strap-down airborne gravimetry systems would be one single accelerometer installed to measure in the approximate vertical component only. The next step to upgrade the system would be to add two tilt meters for the horizontal components. SAGS-2.2 holds the maximum configuration, three Q-Flex accelerometers in an orthogonal system with the best sensor mounted in the vertical component. In an aircraft environment vibrations easily have much larger amplitudes than the gravity signal that is to be determined. They are comparable in amplitude to the aircraft kinematic induced acceleration with only a small frequency gap in between. The SAGS principle of measurement (meaning accelerometer reference, attitude and position reference have a fixed relation) does not allow high damping ranges (below 5 mm). It is still a difficult task to design an optimized vibration-damping platform that suits a range of different aircraft. Three different acceleration signal sources merged have to be processed by SAGS: vibration, aircraft kinematics and the gravity field. As discussed above, vibrations are physically damped by the platform design. The lasting signal is measured by the Q-Flex accelerometers and analogue-filtered. The filtered signal can either be digitized by a frequency counter or by an analogue-to-digital converter. The derived signal on each way now can be filtered digitally and reduced by the accelerations computed from the GPS-signal from aircraft antennas.

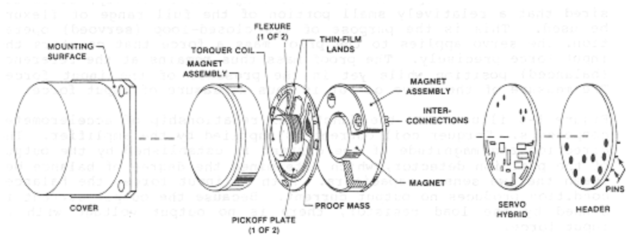

Figure 5.6: Q-Flex accelerometer

Sensor unit physical size:	42 cm (16.5”) W x 42 cm (16.5”) D x 34 cm (13.4”) H
Sensor unit weight:	49.5 kg (109 lbs.) (including SINS & VIP)
Sensor power requirements:	60 Watts @ 12 VDC (initial heating)
	15 Watts @ 12 VDC (standard operation)
Meinberg clock physical size:	24 cm (9.5”) W x 36 cm (14.2”) D x 14 cm (5.5”) H
Meinberg clock weight:	4.5 kg (9.9 lbs.)
Clock power requirements:	less than 10 Watts @ 12 VDC or 220 VAC
Data logger – notebook:	Type Kontron / Panasonic CF25 or
Data logger physical size:	30 cm (12") W x 30 cm (12") D x 30 cm (12") H
Data logger weight:	4 kg (8.8 lbs.)
Data logger power requirements:	max. 40 Watts @ 220 VAC

Table 5.3: Physical properties of the SAGS 2.2 strap-down gravity meter system

5.3 IGI inertial navigation system CAE-10-01

The standard system from IGI is a guidance, positioning and management system for aerial survey missions named CCNS4. A special version named CAE-10-01 was adapted to GFZ requirements. The main task of the system is not the flight management but the attitude measurement of the aircraft. Thus, most flight control options were omitted in favor of best control over the raw data. The basic system consists of the central computer unit that handles the data flow, acquisition and visualization. The CAE-10-01 can either be used as a sub-unit of the CCNS4 system with status reports displayed on the CCNS4 information pages or as a stand-alone data acquisition unit. For all airborne missions of the GFZ so far the system was operated in the later mode. This special version CAE-10-01 can be used to control either remote sensing systems or just be taken for aircraft attitude measurements. Together with the AEROcontrol system, based on DGPS and information from an inertial measurement unit (IMU) - it allows real time and post processing of sensor or aircraft frame positions for given instants. The system allows the determination of the elements of exterior orientation (ϕ, ω, κ and x/y/z). Heading information with accuracy of 1/10° and pitch as well as roll information are being furnished with an accuracy of 1/100°.

The principal navigation sensors of the AEROcontrol system are a 12 channel parallel L1/L2 RX GPS receiver (Novatel OEM4) on 1 Hz and a dry tuned gyro with a separate sensor head (modified LITEF LCR 88) on 50 Hz (Figure 5.7). The data output is the system time, the angel increments and the velocity increments both in the x-, y-, z-axes with 50 Hz. Additionally, the system time, the GPS week second and 5 optional channels are recorded with 1 Hz. This IMU and optional sensor data is stored parallel with the Ashtech GPS data on a portable flash disk. Events are time stamped and marked in an extra data channel (waypoints, power settings, etc.). The data can be post-processed using the IGI AEROoffice software – having computed the kinematic DGPS positions from the Novatel OEM4 GPS receiver first. Technical details are given in Table 5.4.

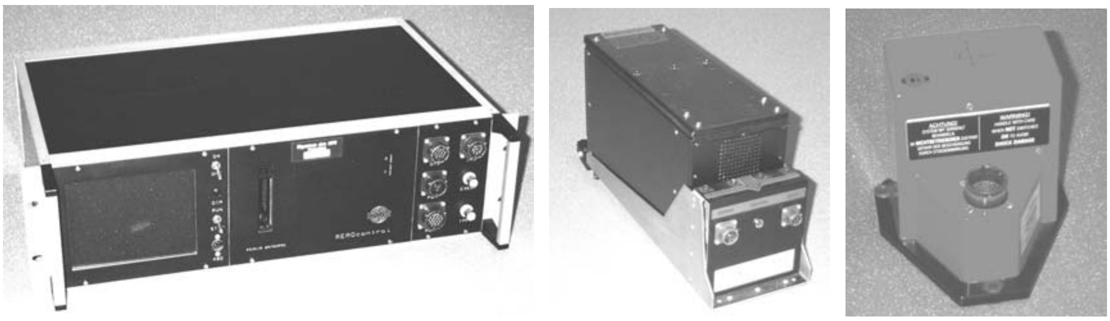

Figure 5.7: IGI inertial navigation system console, electronics box and sensor head

IMU sensor unit physical size:	20 cm (7,9") W x 20 cm (7,9") D x 25 cm (9,8") H
IMU sensor unit weight:	49.5 kg (109 lbs.) (without cable)
IMU E-box unit physical size:	20 cm (7,9") W x 35 cm (13,8") D x 25 cm (9,8") H
IMU E-box unit weight:	49.5 kg (109 lbs.) (without cables)
IMU E-box power requirements:	60 Watts @ 12 VDC (initial heating)
	15 Watts @ 12 VDC (standard operation)
CAE-10-01 unit physical size:	48,3 cm (19,0") W x 36 cm (14.2") D x 18 cm (7,1") H
CAE-10-01 unit weight:	4.5 kg (9.9 lbs.) (without cables)
CAE-10-01 power requirements:	less than 10 Watts @ 12 VDC or 220 VAC

Table 5.4: Physical properties of the IGI inertial navigation system.

5.4 Novatel OEM4 GPS receivers

In the CHICAGO survey, for the first time in the GFZ airborne gravity campaigns a homogeneous set of Novatel OEM4 GPS receivers was used. This setting improved the GPS processing significantly.

The Novatel OEM4 receivers consist only of a receiver card, a power supply unit and a case to shield from external electromagnetic or magnetic fields (Figure 5.8). Keyboard, display and memory were not included. Therefore, a special compact computer unit had to be designed for usage in the aircraft and on ground. The computer system was designed and assembled at GFZ Potsdam. It bases on PC-104 industry computer components. The software to program and control the GPS receivers was developed by Roman Gallas and Hartmut Pflug at GFZ Potsdam. It handles the operation in a way that does not require any external keyboard and user inputs. A LCD-display with just four lines with 20 characters each is used to write out the operation conditions. Moreover, three LED's are used for the quick control of the system status. Technical details are given Tables 5.5 and 5.6


Figure 5.8: Novatel OEM4 GPS receiver and antennas. For the aircraft installation, the small flat antenna in left front is used, for the ground reference stations the in the right front in conjunction with the choke ring next to it.

Physical size:	11.1 cm (4.4") W x 20.8 cm (8.2") D x 5.4 cm (2.1") H
Receiver weight:	0.98 kg (2.2 lbs)
Power requirements:	3.3 Watts (typical), 4 Watts (maximum) @ 10 to 36 VDC
Env. operating temperature:	-40°C to +75°C (-40°F to +167°F)
Storage temperature:	-45°C to +95°C (-49°F to +203°F)
Humidity:	95%, non-condensing
Interfaces:	RS-232 ports, 2 ports 230 to 300 bps, one port 400 bps
Strobes:	PPS, mark in, mark out, position valid, frequency out

Table 5.5: Physical properties and hardware description of the Novatel OEM4 GPS receivers.

Single point L1:	1.8 m CEP
Single point L1/L2:	1.5 m CEP
DGPS (L1, C/A):	0.45 m CEP
L1, C/A code precision:	6 cm RMS
L2, P-code precision:	25 cm RMS (AS on)
L1 carrier phase precision:	0.75 mm RMS (differential channel)
L2 carrier phase precision:	2 mm RMS (differential channel)
Measurements rates:	20 Hz
Position rates:	20 Hz
L1 signal re-acquisition:	0.5 s (typical)
L2 signal re-acquisition:	6 s (typical)
Time accuracy:	102 ns RMS
Velocity accuracy:	0.03 m/s RMS
Acceleration dynamics:	10 g
Vibration dynamics:	4 g (sustained tracking)
Velocity dynamics:	515 m/s maximum

Table 5.6: Performance parameters of the Novatel OEM4 GPS receivers.

The computer system consists of the following modules: power supply, CPU card (ELAN SC400/410 processor, 32 MB RAM), compact flash-card as memory unit for the operating system, serial interface card with four additional ports, digital IO-card (control of external switch settings and status control) and a PCMCIA module for compact flash-cards as portable memory unit for acquired data.

In all previous airborne gravity campaigns large problems occurred with the use of laptops or conventional hard-discs. Especially the disturbances during start and landing often lead to system breakdowns. Moreover, conventional hard-discs only work reliably up to elevations of 10000 ft. Beyond this mark, the air pressure for most products is too low to let the read/write head hover safely over the physical disc. In our solution, only flash-discs are used for both the operating system and the data storage. The flash cards can be easily put in and out of the computer system and their contents can be re-written or copied on any laptop system. In the procedure we used during the survey, the flash cards containing the flight data were extracted from the system and replaced with new ones between flights. During the flights, the data was copied by the ground crew to laptops and then burned on CDs. This operation minimized the probability of data losses and ensured that flights could be performed twice a day if necessary.

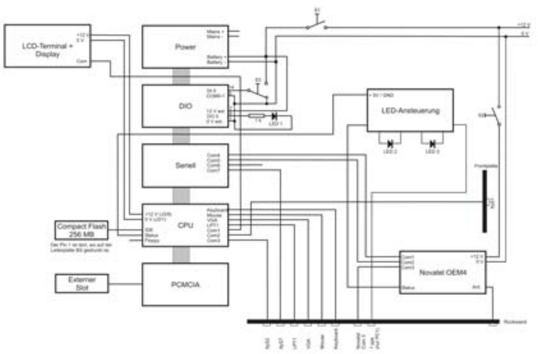

Figure 5.9: Novatel OEM4 GPS receiver embedded in the PC104 computer system.

SUSE Linux 6.3 was chosen as the operating system. It is much more stable than Windows systems and provides much better working environments for automatic scripts etc. Later Linux versions could not be used due to limitations of the CPU board (no co-processor, low RAM). An overview about the internal architecture is given in Figure 5.9. The system is configured in a way that after switching power on the system is booted automatically. The most important boot messages are linked to the display. When the operating system is ready, the data flash-disc is mounted automatically. After this, the GPS receiver is initialized with the settings defined for the survey. Two serial links to the GPS receiver, one for command settings and one for data acquisition achieve this. When the receiver is ready, the system displays a message and waits for the user to activate the data acquisition by second “on”-switch. All data is stored on the external flash-disc. Important information like GPS position, GPS time, duration of measurement and memory allocation are displayed with updates of 10 seconds. When the “on”-switch is set off, the system automatically stops the data acquisition, stops the receiver and shuts down the computer. When all systems are off, the display is powered off as well. Three LED’s supply the user with quick status controls: LED1: data acquisition is running, LED2: receiver has valid position, LED3: error in GPS receiver.

One of the serial ports is configured to be a serial console. Here, a laptop can be connected and via a terminal program problems can be fixed or software upgrades can be transferred. For more extensive work in the laboratory, a monitor and keyboard can be connected to the PC104 computer system.

5.5 Riegl laser altimeter

The Riegl distance meter (Figure 5.10) enables laser range measurements even under conditions of bad visibility. Generally spoken, the distance meter provides the range of the last target, even if the measuring beam partially hits or penetrates other targets before (Figure 5.11). Thus, the technique is addressed as last pulse detection.

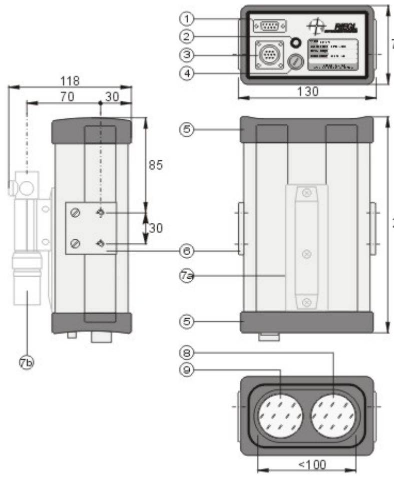

Figure 5.10: Riegl laser altimeter (physical units are mm).

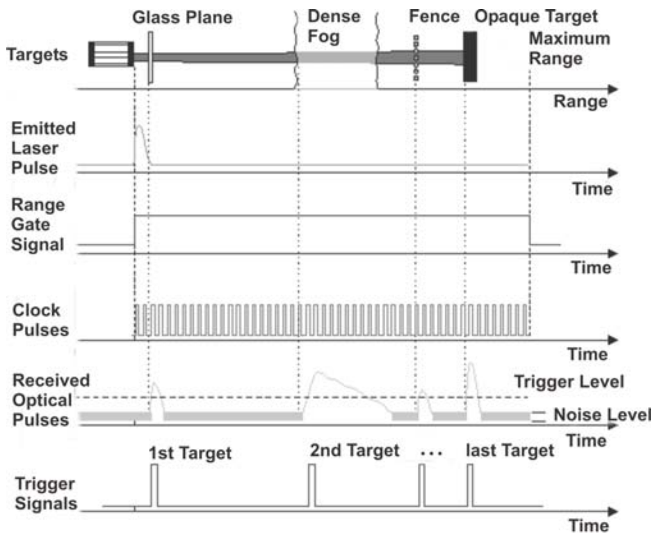

Figure 5.11: Last Pulse Detection

The main features of the laser distance meter are: light weight and stable metal housing, short high-energy infrared light pulses provide excellent interference immunity, measurements are fast offering update rates as high as 200 Hz / 2 kHz / 12 kHz, measurements can be taken through glass windows, narrow measurement beam with very low divergence providing good spatial resolution, measurements can be taken to almost any surface regardless of the incident beam angle or surface characteristics and measurements are unaffected by the temperature of the material surface and of temperature gradients in the medium between the sensor and the target surface. For technical details see Tables 5.7 and 5.8.

Physical size:	13 cm (5") W x 20 cm (8") D x 7.6 cm (3") H

Weight:	approx. 1.5 kg (3.3 lbs)
Power requirement:	approx. 10 Watt @ 11-18 Volts DC protecting circuitry for over-voltage and reverse polarity
Option 20-28 VDC:	external pre-stabilization and protecting module STAB95 (used on aircraft installation)
Option 220 VAC	external power supply module VNG95 (not yet available at GFZ)
Temperature range:	Operation -10° C to +50° C Storage -20° C to +60° C
Protection class:	IP64
Data interfaces:	RS232 & RS422 (selectable, standard for all types) Baud rate selectable between 150 Baud and 19200 Baud, further 38.4 kBaud and 115.2 kBaud RS422 high speed (available for VHS types only) 115.2 kBaud in "high speed" mode, 19.2 kBaud in "adjust" mode, asynchronous Parallel interface (extended capabilities port)
Available data output: (options not for all types)	Analogue current, 4-20 mA [1], not galvanically isolated, resolution 16 Bit, linearity 0.05 ‰ of full scale
Switching output	2 x PNP transistor driver [2] built-in thermal and short-circuit protection switching current 250 mA maximum switching voltage = supply voltage

[1] operating range selectable via serial interface
[2] switching points adjustable via serial interface

Table 5.7: Physical properties of the Riegl laser altimeter

Measuring range (depending on the reflection coefficient of the target):	
good, diffusely reflecting targets, reflectivity ³:	80 up to 500 m [1]
bad, diffusely reflecting targets, reflectivity ³ 10%:	up to 150 m [1)]
reflecting foil [2] or plastic cat's-eye reflectors:	> 1000 m
Minimum distance:	typically 5 - 10 m
Distance measurement accuracy [3]:	typically ±5 cm Worst-case ±10 cm
Measuring time (ms or s) [4]:	10ms / 20ms / 50ms / 0.1 / 0.2 / 0.5 / 1 / 2
Statistical deviation (cm) [5]:	±10 / ±7 / ±5 / ±3 / ±2 / ±1.5 / ±1 / ±0.7
Resolution [5, 6]:	10 / 10 / 5 / 5 / 2 / 2 / 1 / 1
Measuring time, typically [4]:	0.5 s
Divergence of the infrared measuring beam [7]:	1.8 mrad
Eye safety class:	according to CENELEC EN 60825-1 (1997)

[1] Typical values for average conditions. In bright sunlight, the operational range is considerably shorter than under an overcast sky. At dawn or at night the range is even higher.
[2] Reflecting foil 3M 2000X or equivalent, minimum dimensions 0.45 x 0.45 m2.
[3] Standard deviation, plus distance depending error < 20 ppm.
[4] Adjustable via RS232.
[5] Depending on measuring time.
[6] Chosen automatically by the internal microprocessor.
[7] 1 mrad corresponds to 10 cm beam width per 100 m of distance.

Table 5.8: Performance parameters of the Riegl laser altimeter

5.7 Computer Systems

The ANGEL system was designed to be a modular system with independent PCs for each sensor unit. The PC units for the GPS receiver have been described in chapter 5.4. A second 19-inch rack unit with three PC104 systems was designed based on Windows'95 operating system (Windows'95 is the only Windows system that does not need a CPU co-processor). This operation system was chosen because the sensor systems control is still based on Windows programs. For future developments we aim to switch as many sensor systems as possible to the Linux environment. The Riegl altimeter system and the strap-down gravity meter were operated by two of the PC104 systems. The third PC104 system was used as a watchdog to control I/O processes. The LaCoste & Romberg gravity meter has its own PC system based on DOS. The IGI inertial navigation system operates similar to the PC104 systems. All sensing systems store the data on flash-memory cards. Only one small operator work place (Figure 5.12) is needed to control the three GPS receivers, the two gravity meters and the laser altimeter. All monitor, mouse and keyboard I/Os are linked to the operator unit and can be switched from one system to any other system by software or hardware keys.

The Meinberg clock used is in the central time trigger unit is basically a static GPS reference system receiving GPS time signals. This corrected time signal is used to initialize and control an internal high quality quartz clock. The highest internal clock rate is 10 MHz. This rate is used to derive trigger signals in between on pulse per minute up to 100 Hz. These signals are used to trigger measurements in different other instruments used with the aerogravimetry ensemble or to control their timing.

5.8 Power distribution and control

The main power sources are the power generators connected to the aircraft engines. The generators supply a noisy, slightly fluctuating 28 VDC. A voltage inverter is used to transform the primary 28 VDC into 230 VAC. This secondary power source provides the PC104 systems and the strap-down gravity meter. The LaCoste & Romberg meter has its own unbreakable power supply unit that is fed with 230 VAC and distributes 115 VAC to the sensor and PC system. The laser altimeter and the central time trigger unit have their own DC/DC converters; both systems can be directly supplied by the primary 28 VDC.

6 Ground equipment

6.1 LaCoste & Romberg G-meter

In order to link the relative airborne gravity measurements to a regional gravity reference system, a LaCoste & Romberg G-meter (Figure 6.1), No. 998, was used. The instrument is owned by the FU Berlin and was operated by Andres Tassara. For more information see Annex 1.

Figure 6.1: LaCoste & Romberg G-meter

6.2 Novatel OEM4 GPS receivers

The ground GPS reference network utilizes the same GPS receivers as already described in chapter 5.4. The data acquisition unit is also based on PC104 components but the internal architecture is organized slightly different (Figure 6.2).

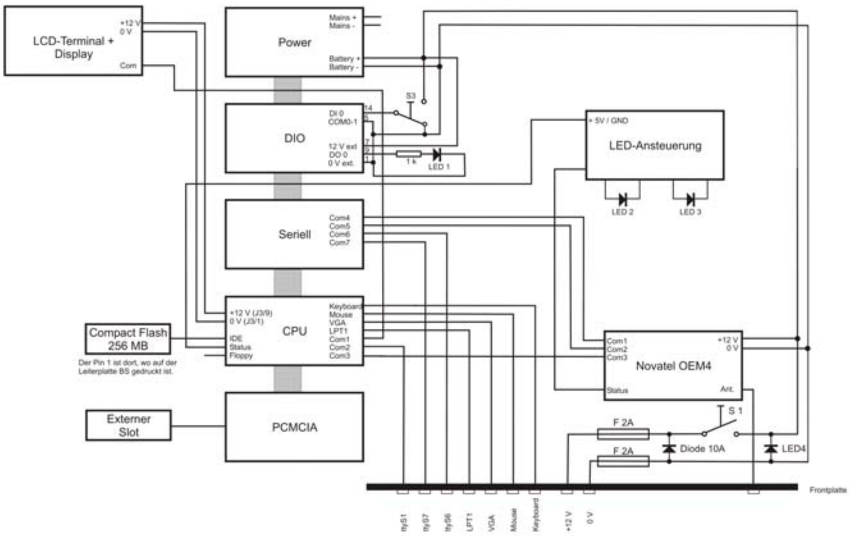

Figure 6.2: Internal architecture of the GFZ GPS ground reference stations.

The GFZ GPS reference station (Figure 6.3) was built by GFZ and Ingenieurbüro Enz in Berlin into a housing that is easy to transport and to handle. All operation devices are placed on the front side of the ground operation unit. A laptop or alternatively, keyboard and monitor can be easily connected to maintain the system. All important boot and operation messages are linked to the operation unit display. The data is stored on a removable flash-memory card.

Figure 6.3: GFZ designed GPS reference station: left: GPS station set-up in Puerto Montt; right: GPS ground operation unit.

6.3 GPS reference station at TIGO

In order to have the possibility to link the GFZ GPS ground stations to a well-established GPS site; the TIGO station was chosen for reference. TIGO is a transportable, integrated geodetic observatory (Figure 6.4) which is located in Concepcion and run by the fundamental station Wettzell of the Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt/Main. TIGO operates a hybrid GPS/Glonass Javad receiver permanently (Figure 6.5). A special tower-like base holds the antenna system. Within the base a tilt meter is installed to control long-term stability. An additional refraction mirror makes it possible to survey the position by electro-optic systems. The GPS/Glonass data of TIGO are supplied to the international GPS service (IGS). Especially for the CHICAGO survey, the Javad receiver was upgraded to 10 Hz measurements. The data was sent to Wettzell via satellite and then posted on an ftp-server for download.

Figure 6.4: TIGO geodetic observatory in Concepcion

Figure 6.5: left: GPS antenna and tower base; right: PC data acquisition unit for 10 Hz GPS data

6.4 Computer systems

Several more computers are needed in a temporal office in order to ensure data storage, quality control etc. One laptop is reserved for data copying, temporal storage and CD-burning. In this case, data copying includes the conversion of binary data of individual sensors into ASCII formats (as the transformation of binary Novatel GPS observation data to RINEX files). This computer needs flash-card readers, CD-burner connection and extended memory. A second laptop is in use for data evaluation as the testing of the quality of GPS data and the computation of first gravity profiles. A third laptop is linked to the Internet in order to download GPS ephemeredes and to function as small mail-server. Another laptop is reserved for the pilots for flight planning and download of meteorological data. For flight planning the internationally used program FliteStar is used. At last, one laptop is necessary to control and maintain the stations in the field and to download long term GPS data at remote stations.

7 Data processing

A schematic image about the concept of airborne gravimetry is given in Figure 7.1. An overview about the aerogravimetry data processing is given in Figure 7.2. In the initial phase of the data processing, the kinematic differential GPS data is computed. In our case we used Trimble Total Control software for this purpose. Only in cases where Trimble Total Control gave no results due to internal errors, the KSG-Soft program [Xu et al, 1998] was used. Comparisons between both software solutions on profiles without errors or data uncertainties showed good agreement. Volker Grund, a GFZ diploma student, did the GPS compilations. The second primary data input is the raw gravity measurement from the LaCoste & Romberg gravity meter. One of the first crucial steps in GPS data processing is the determination of time offsets between GPS and other input data. In order to accurately estimate the time offset the GPS time is defined as correct and fixed. From the GPS heights the vertical aircraft acceleration are computed. This is the reference for the time correlations to follow. The data stream (for instance of the gravity data) is first shifted within a time window of some minutes and later on in window of some seconds in order to find the best time correlation. Finally, the best time correction over the full profile length is determined, assuming a static shift. If for some reason time fluctuations are suspected in a time series, a dynamic data shift for each epoch based on a 30 seconds window is can be optionally computed. The more and the steeper gradients occur in the data set, the better the time correlation will work. Of course, such strong disturbances are generally not desirable. The software is able to fit the data streams up to a 1/100 second. After the synchronization is ensured, the Eötvös correction, tilt correction and, if required, free-air reduction is computed. All these computations are still based on the unfiltered, common 1 Hz data frame. Only after all corrections and reductions are applied, the data is low-pass filtered using a Butterworth filter with a cut-off wavelength of 200 seconds, translating to a mean spatial resolution of about 6.5 km. Details of the processing are given in Meyer et al. [2003].

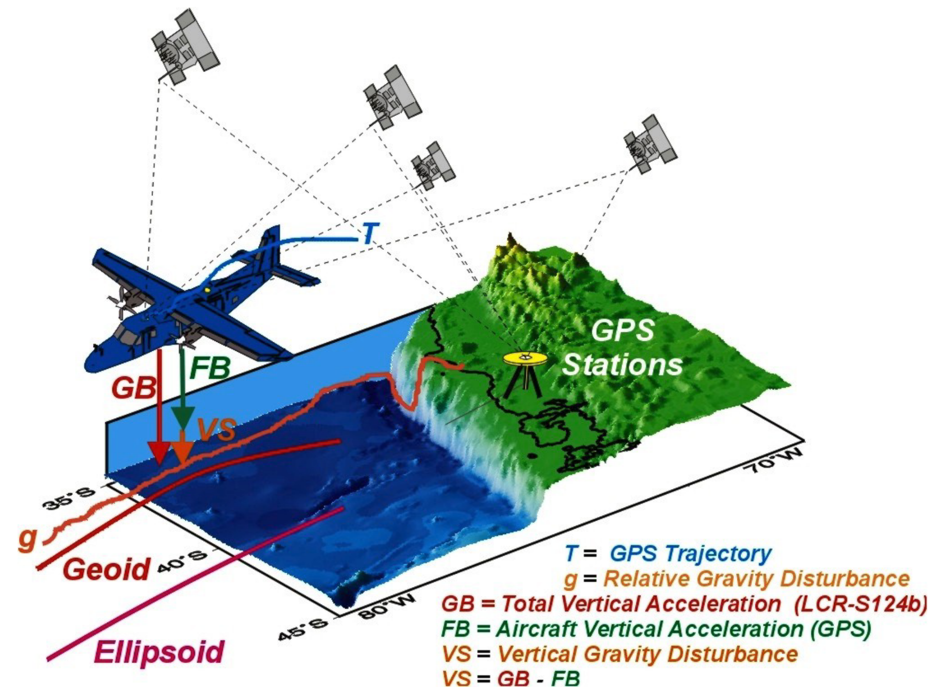

Figure 7.1: Overview about the concept of airborne gravimetry.

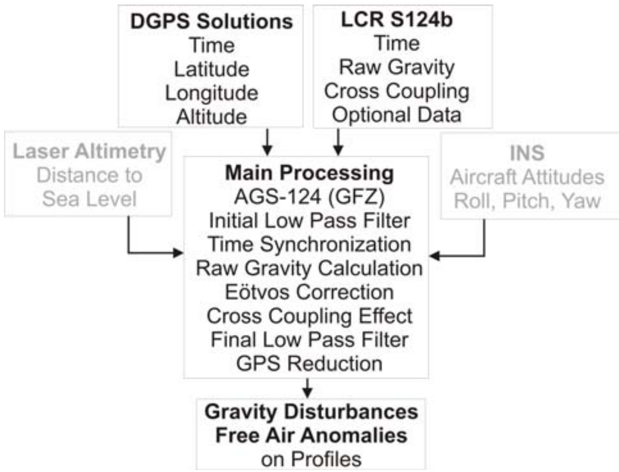

Figure 7.2: Overview about airborne gravimetry processing. Optional data inputs to the processing are given in gray.

For ground truth comparison three data sets were blended into one ground truth grid. The data sets are altimetry derived KMS'99 free-air values over the ocean [Andersen & Knudsen, 1998], onshore free-air grid values from the University of Sao Paulo, supplied by Prof. Denizar Blitzkow and free-air land measurements supplied by the SFB267.

Due to some instrument uncertainties and small performance variations due to particle contamination of the air damper system, some misfit between internal sensor orientation and sensor case horizontation and therefore non-optimized cross coupling and tilt correction some uncertainties remain with the data quality of the LaCoste & Romberg S124b data. The instruments was cleaned, maintained and re-calibrated right after the survey by the manufacturer. The margin of the data uncertainty ranges from less than 0.1 mGal during ground base readings and 10 to 15 mGal connected to strong aircraft disturbances in the airborne mode.

In order to keep the resulting data comparable between profiles, a constant k-factor of 39.0 was used to scale the gravity data instead of optimizing the k-factor for each flight. The gravity-processing program was extended by a routine to model the tilt correction in both free axes of the meter. Using this option for individual profiles, the tilt correction could be improved up to 2 mGal (corresponding to the rms difference between airborne and ground truth free-air gravity data). In order to keep profiles comparable, this option was not used in the final processing. Offshore and onshore free-air correction was computed without including terrain effects.

In conclusion, the effect of some small meter errors multiplied by relatively large aircraft disturbances due to the lack of an auto-pilot (vertical aircraft accelerations were a factor of 5 to 10 higher than with a comparable aircraft using an auto-pilot) resulted in a broadened error margin for the airborne gravity data. The quality of the individual profiles is discussed in the subsequent chapters. With the maintained LaCoste & Romberg S124b system and a Twin Otter equipped with an autopilot system, the data quality will be significantly enhanced.

In order to fix the relative airborne gravity measurements to regional gravity system, a measurement link was applied using a LaCoste & Romberg G-meter on the site of the base reading of the airborne system and an absolute gravity station in the vicinity of the airport. Although this data link was carefully applied, a constant mean shift of 158 mGal had to subtracted from the airborne data to fit offshore and onshore ground truth measurements.

The strap-down gravity meter data will be presented in a future publication and is not discussed here.

8 Offshore survey flight results

8.1 Introduction

The survey flights offshore the Chilean coast were the first part of the CHICAGO survey. The flights were unusually long for the cockpit crew and due to the fact that no autopilot was available also extraordinary straining. At the beginning, the flight crew and the operators therefore had to make clear what essential demands had to be respected on both sides. The pilots had to physically learn what flight conditions the gravity system needed for proper results. The operators needed to understand the special aircraft handling and the pilot's capabilities to maintain straight and level survey flights. After a while, a mutual understanding developed which allowed best possible flight conditions. A small group of three pilots was selected for the CHICAGO flights. All three pilots were present at all survey flights and cockpit seats where changed during turns between profiles. This arrangement was made in order to ensure that the pilot in command was relaxed and could concentrate as good as possible on the survey flight. Requirements for the flight performance were straight lines with small heading deviations if needed, a more or less constant ground speed and, most important, minimum variations in altitude, pitch and roll. Waypoints and headings in the cockpit were computed and displayed by a Garmin GPS cockpit navigation aid. The altitude was controlled by a barometric altimeter system. After some survey flights, the pilots got a very good feeling for what maneuvers should be avoided and how to keep the aircraft stable. Nevertheless, weather conditions were good but not always perfect and so the pilots had a difficult task to fulfill. The cockpit crew was extremely careful to maintain best possible flight conditions and developed a high skill and feeling for the requirements of stable gravimetric survey flights. We found that the best parameter for the pilots to check the flight performance was the cross coupling error of the LaCoste & Romberg gravity meter system. Therefore, these numbers were reported to the cockpit. For future surveys a cockpit display informing the pilots about the cross coupling errors will be available. Due to the limited survey time and flight hours, there was no second chance for any of the flights. In the end we found that we got reasonably good results from the survey flight, which were basically guaranteed by the efforts of the flight crew but an autopilot system would be very desirable for a second airborne gravity campaign. The autopilot would make the work of the pilots much easier (the pilots were physically and mentally exhausted after the survey) and would ensure more stable results for the measurements. With the limited money resources available for the survey planning, aircraft installation and flight hours the applied procedure was the best possible compromise we could achieve. In the subsequent pages, the flight paths of the offshore survey flights are displayed. Moreover, the most essential parameters and the results from the processing of the LaCoste & Romberg instrument are given, including bathymetry from ETOPO'2 and the flight attitudes (pitch, yaw, roll and altitude). The processed profile figures are highlighted in the midst of the figures to show the extent of the profile that gave useful results for further investigations. The gray "curtains" left and right of the highlighted middle section therefore only show the onset of the profile and the filter edges of the Butterworth filter (for all profiles set to 200 seconds, translating to a resolution of about 6.5 kilometers geological half wavelength considering a mean ground speed of about 240 km/h). All flights except the ones around Mocha Island (ANGEL-02-05, 500 meters altitude) were performed at about 300 meters (just underneath the normal daily cloud layers). Remaining errors and uncertainties are discussed with the individual profiles. In general, the vertical aircraft accelerations are about 5 to 10 times higher than in surveys with similar aircraft using autopilots. This and some minor instrument errors of the LaCoste & Romberg S124b sensor lead to an error spectrum that is a little noisier than usual for such kind of airborne surveys.

Offshore reference data was taken from the KMS'99 free air gravity solution [Andersen et al. 1999].

Absolute gravity point at Temuco airport:	980030.65 mGal
Relative G-meter reading at Temuco airport absolute gravity point:	3615.08 mGal
Relative G-meter reading at Temuco survey aircraft site:	3610.58 mGal
Related absolute gravity at Temuco survey aircraft site:	980026.15 mGal
Base reading of LaCoste & Romberg sensor at Temuco survey aircraft site:	10854.5 mGal

Table 8.1: Tie between LaCoste & Romberg S124b observations and local absolute gravity

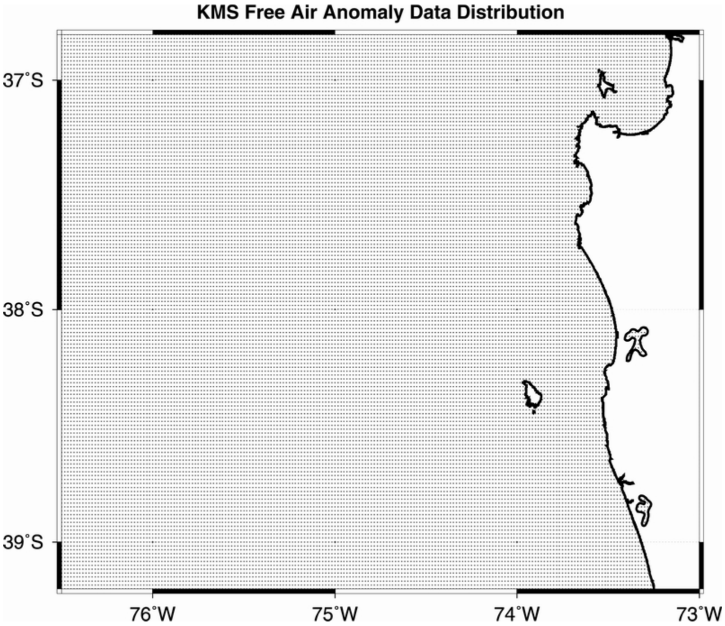

Figure 8.1: KMS'99 free-air gravity data distribution. The data was interpolated to a regular 10' x 10' grid cut off by a land-mask defined by the shown shoreline from GMT.

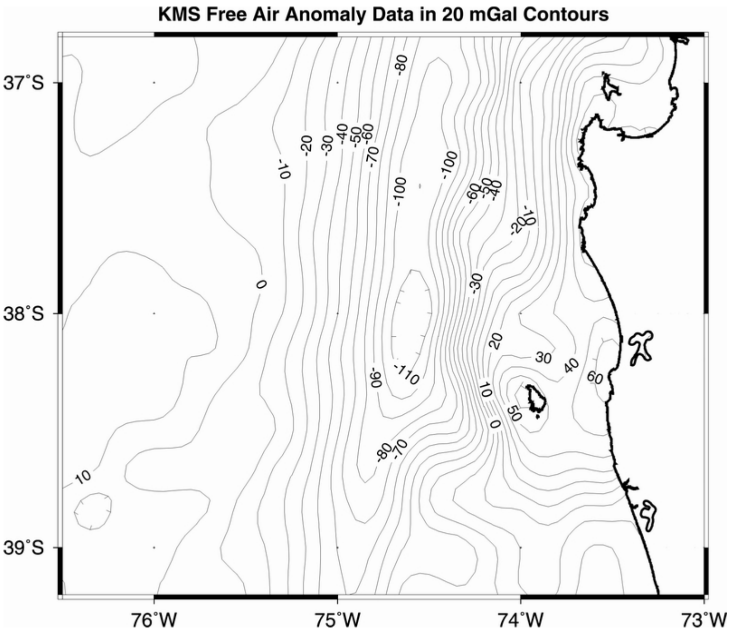

Figure 8.2: KMS'99 free-air gravity data contours based on a 3' x 3' grid cell size.

8.2 Flight ANGEL-02-02

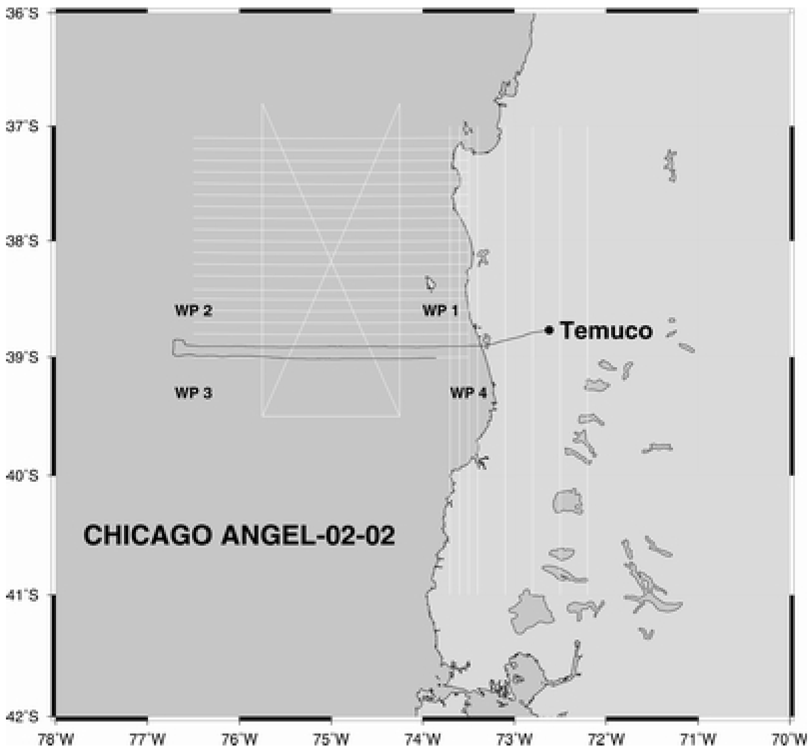

Figure 8.3: Flight path of survey flight ANGEL-02-02.

The flight ANGEL-02-02 was the first survey and measurement flight for the complete team including the aircraft crew. Only one flight had been carried out before to scale the strap-down gravity meter system and to find it's components position in the aircraft by performing dynamic flight maneuvers in different heading directions. Therefore, this flight was the first real test for the crew and equipment. The first part of the flight was stable and weather conditions were fine. We observed a calm and steady wind from WSW direction. The flight altitude was relatively stable on both profiles. As shown in Figure 8.3, the last part of the survey profile could not be computed in terms of the kinematic DGPS positions due to problems with the base station at Temuco.

Profile ANGEL-02-02-01 is heading in EW-direction. It shows obvious differences to ground truth data in the first part of it, where the airborne solution is significantly below the values of the long wavelength KMS'99 solution over the shelf area (Figure 8.4). This difference mainly accounts for the RMS difference of 16.41 mGal. Nevertheless, this feature was stable in all stages of processing and we therefore believe it corresponds to real geophysical sources. The profile ANGEL-02-02-02 south of it is heavily disturbed at its beginning. All significant gravity meter parameters show highly anomalous behavior in at least the first 1200 seconds. Although the pattern seems to be very awkward, it is easily explained. A pilot on his way back from the cockpit into the cabin touched the gravity meter sensor and therefore gave it a shock sequence that has nothing in common with all other aircraft attitudes. After this gravity meter parameters needed a long time settle back to normal conditions. Moreover, the flight stability was not as stable as desired for the rest of the flight (as it can be observed in the Eötvös correction). Therefore, this profile is one of the most problematic ones of the survey. Nevertheless, events like this are to be expected on the first survey flight with an until now un-experienced crew.

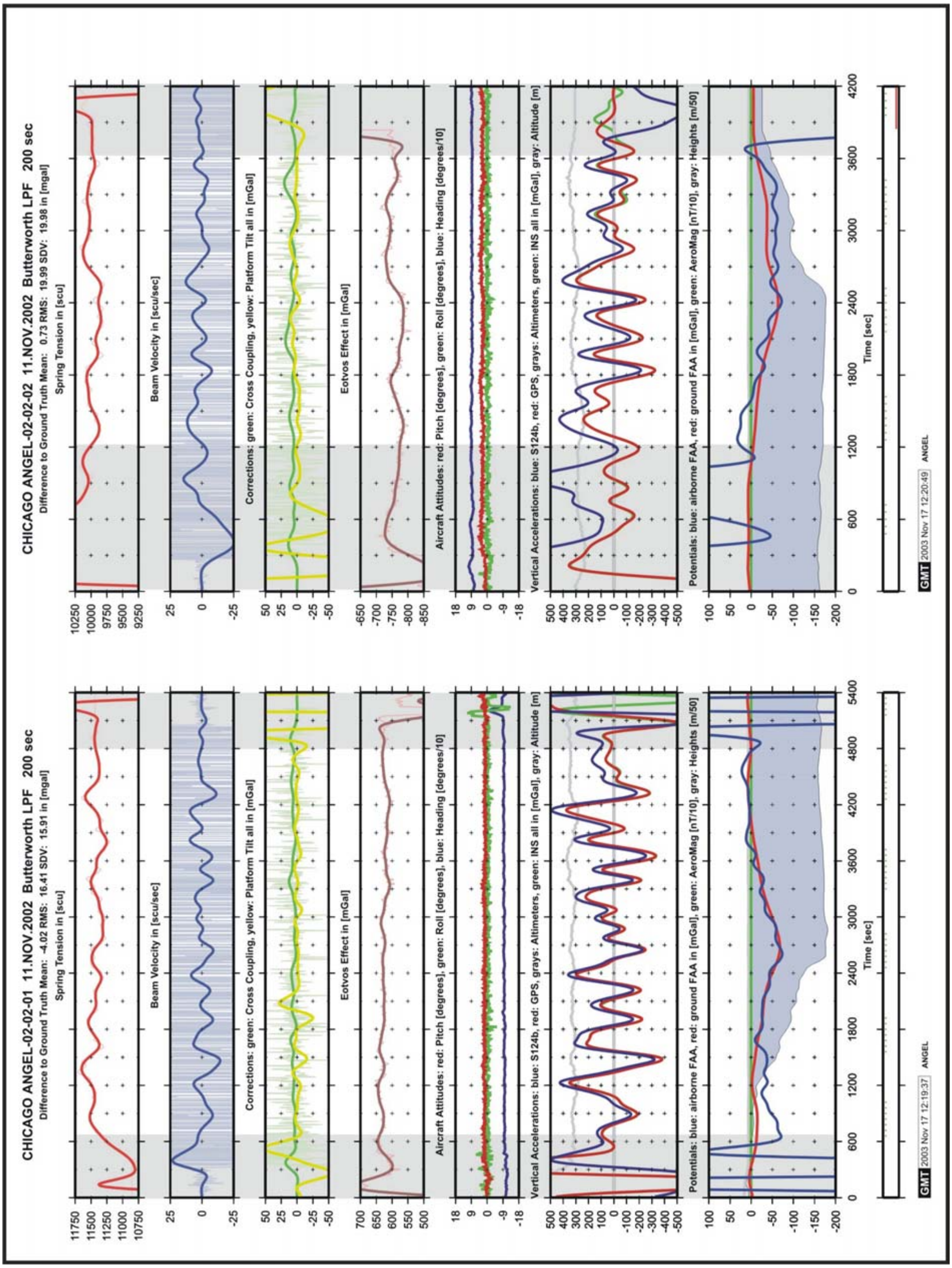

Figure 8.4: Profile data of survey flight ANGEL-02-02.

8.3 Flight ANGEL-02-03

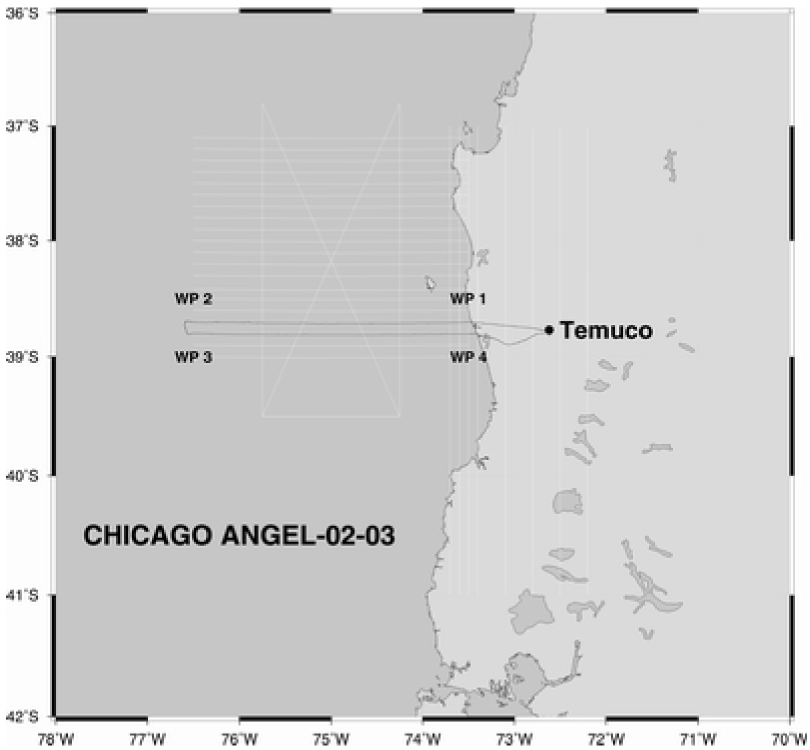

Figure 8.5: Flight path of survey flight ANGEL-02-03.

Survey flight ANGEL-02-03 (Figure 8.5) shows good flight conditions and gravity results for the first profile, heading EW. As in profile ANGEL-02-02-01 the current profile ANGEL-02-03-01 shows a gravity low over the shelf area (as does the profile in between, ANGEL-02-03-02). The Eötvös effect is small and the flight altitude very stable. Therefore, this profile is already a good example of how good the measurements can be under the given conditions. The vertical accelerations are still about 5 times higher than comparable flights using an autopilot and a CASA Aviocar aircraft as applied in an airborne gravity survey over the Azores. We still have to keep in mind that the KMS'99 data is derived from altimeter data only and have a wavelength resolution of about 24 km instead of 6 km geological half wavelength in the airborne data. From this we deduce that when a rough gravity signal is to be expected from the type of oceanic crust and bathymetry as we have it here, an RMS difference of 16 to 17 mGal is to be expected (Figure 8.6).

Profile ANGEL-02-03-02 shows some more disturbances in the flight pattern. Moreover, the spring tension value for the LaCoste & Romberg meter was not pre-set at the begin of the profile so that the sensor needed another 600 seconds to properly adjust. At about 1800 seconds, an "abrupt" correction in the heading was performed, at about 2400 seconds an "abrupt" height correction. Whereas the heading correction is well corrected for, the effect from the "sudden" altitude change can be well observed in the vertical accelerations.

Both profiles show that the 200 seconds Butterworth filter as applied to the airborne gravity data is the minimum low-pass filter due to the roughness of the flight conditions.

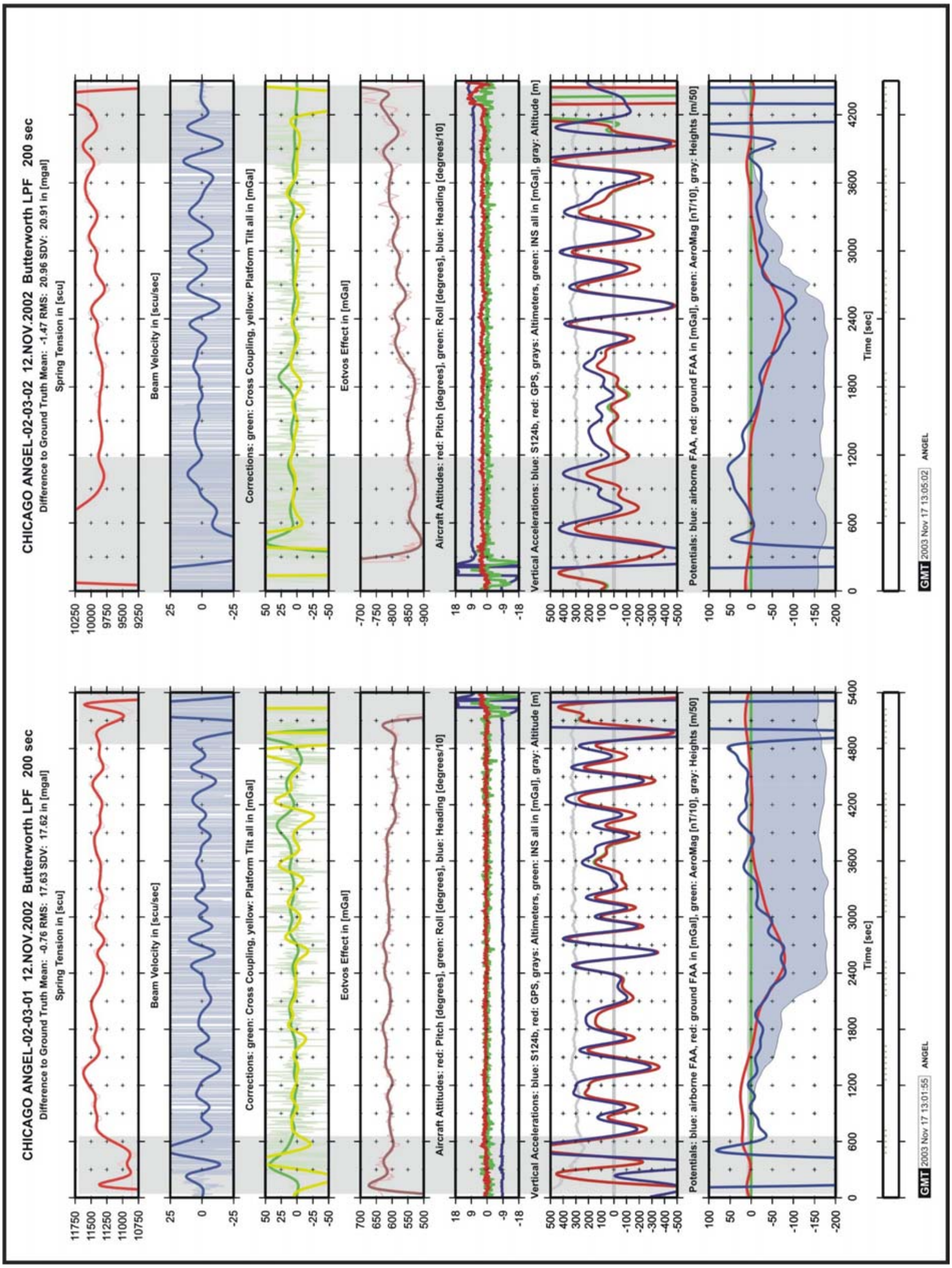

Figure 8.6: Profile data of survey flight ANGEL-02-03.

8.4 Flight ANGEL-02-04

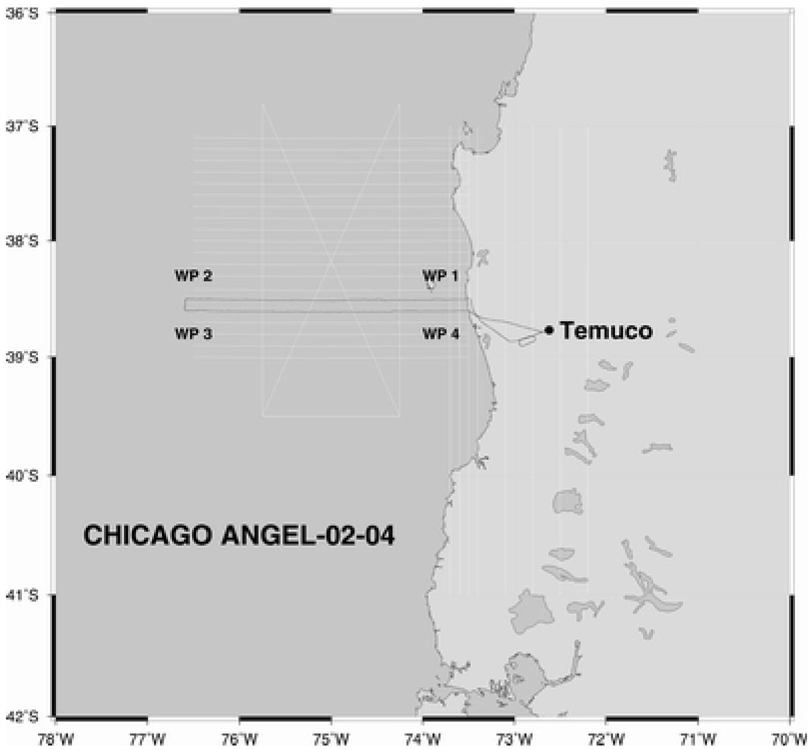

Figure 8.7: Flight path of survey flight ANGEL-02-04.

Mainly due to rougher weather conditions than in the previous flights, survey flight ANGEL-02-04 (Figure 8.7) shows some higher disturbances especially in the Eötvös correction and the platform corrections. Especially the data sequence of profile ANGEL-02-04-01 between 1800 and 2500 seconds leads to a large residual error in the data sequence (Figure 8.8). A sharp tilt in both direction and height leads to extremely large vertical accelerations of more than 1000 mGal peak to peak even in the low-pass filtered data. The rest of the profile is fine and as good as can be under the given circumstances. The example shows clearly, how a singular event can affect an otherwise good profile.

Profile ANGEL-02-04-02 shows also rougher flight attitudes than in the previous profiles but still shows reasonably good results in total (Figure 8.8).

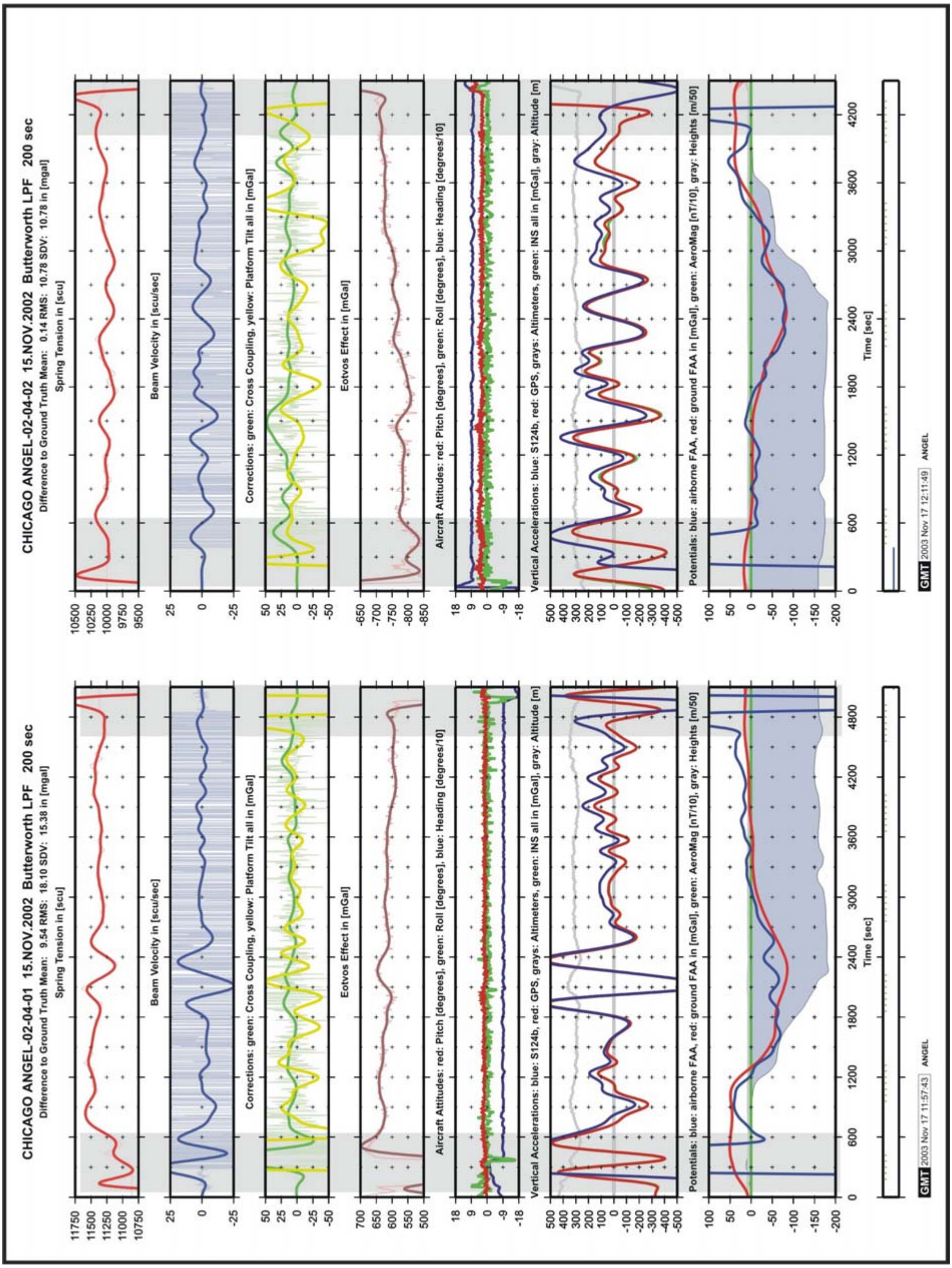

Figure 8.8: Profile data of survey flight ANGEL-02-04.

8.5 Flight ANGEL-02-05

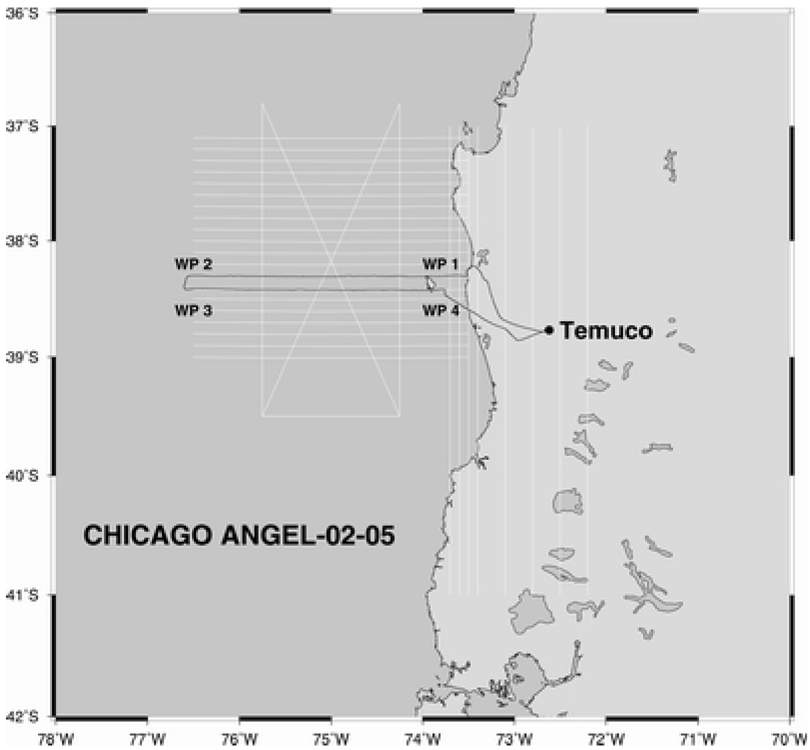

Figure 8.9: Flight path of survey flight ANGEL-02-05.

Survey flight ANGEL-02-05 is the only flight offshore that was flown in an altitude of 500 meters above sea level instead of 300 meters (Figure 8.9). The reason for this is Mocha Island. The island was touched by the flight lines just on its northern and southern edges.

Profile ANGEL-02-05-01 showed good flight conditions with reasonably good gravity data as a result (Figure 8.10). Unfortunately, profile ANGEL-08-05-02 shows two large disturbances in the gravity meter that are only re-adjusted close to the end of the profile. The first disturbance is caused by the effect that the gravity meter was not "clamped" during the turn from the first to the second profile, meaning that measuring beam was not fixed in the zero position and then released at the begin of the profile. The impetus of the turn shifted the beam of the meter to highly positive positions that could not be recovered in due time. The physical cause of the second disturbance is not known. Interpreting the gravity meter parameters a shock on the meter itself might be the reason. The first event was an operator fault, which can only be avoided if two operators are on board controlling each other or by switching to a fully digital operating system for the meter including automatic routines to secure the gravity meter in turns. The lack of any log entries for second impact on the meter may also hint towards another error source. In cases that the common data and power cable of the meter was suddenly shifted, a comparable effects occurs due to the sudden induction change. This effect is known well for LaCoste & Romberg meters and can only be avoided by changing the system to a fully digital one, as it is available since about one year.

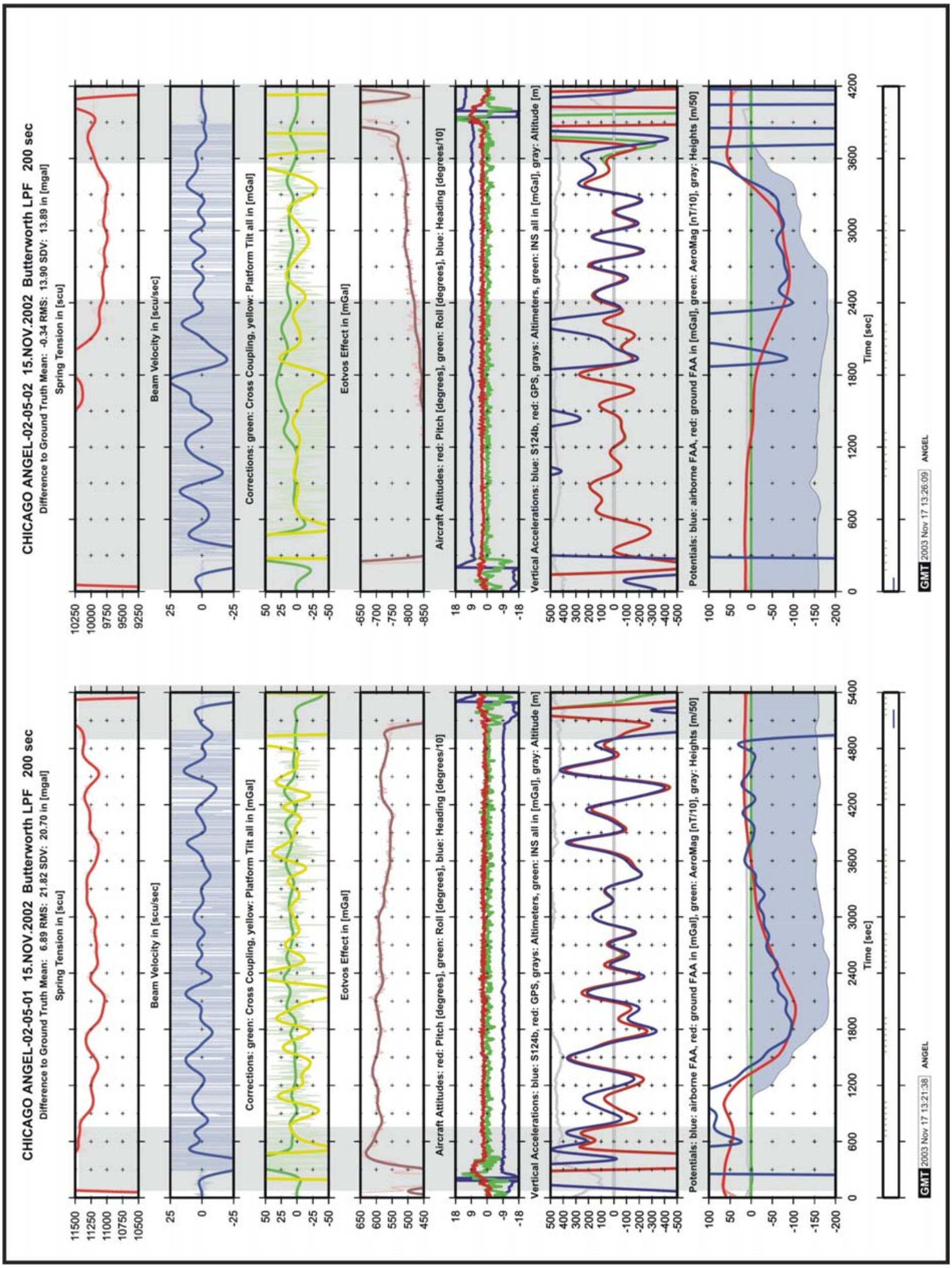

Figure 8.10: Profile data of survey flight ANGEL-02-05.

8.6 Flight ANGEL-02-06

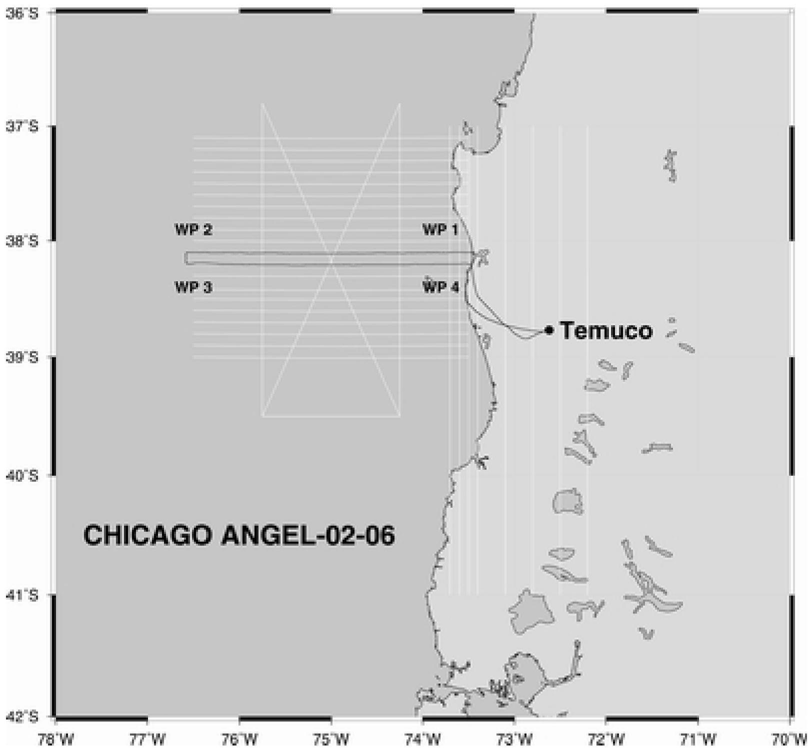

Figure 8.11: Flight path of survey flight ANGEL-02-06.

Flight ANGEL-02-06 (Figure 8.11) shows a good data quality over the whole range of both profiles (Figure 8.12). The first profile, ANGEL-02-06-01, shows a very good match to the ground truth data up to observation second 3600. About this time some large disturbance are monitored on the aircraft (bump in Eötvös correction, high attitude deviations), which could not be corrected as properly as desired. We could speculate that if such disturbances occur close to the coast (and therefore closer to the GPS reference station), the correction leads to better results, because the uncertainties in the GPS solutions are smaller than those far off the coastline. Profile ANGEL-02-06-02 contradicts this assumption. Here, a very large vertical disturbance was nicely absorbed by the correction techniques applied. We therefore strongly believe that some small irregularities in the meter as they were found during the maintenance check are responsible for most of these effects.

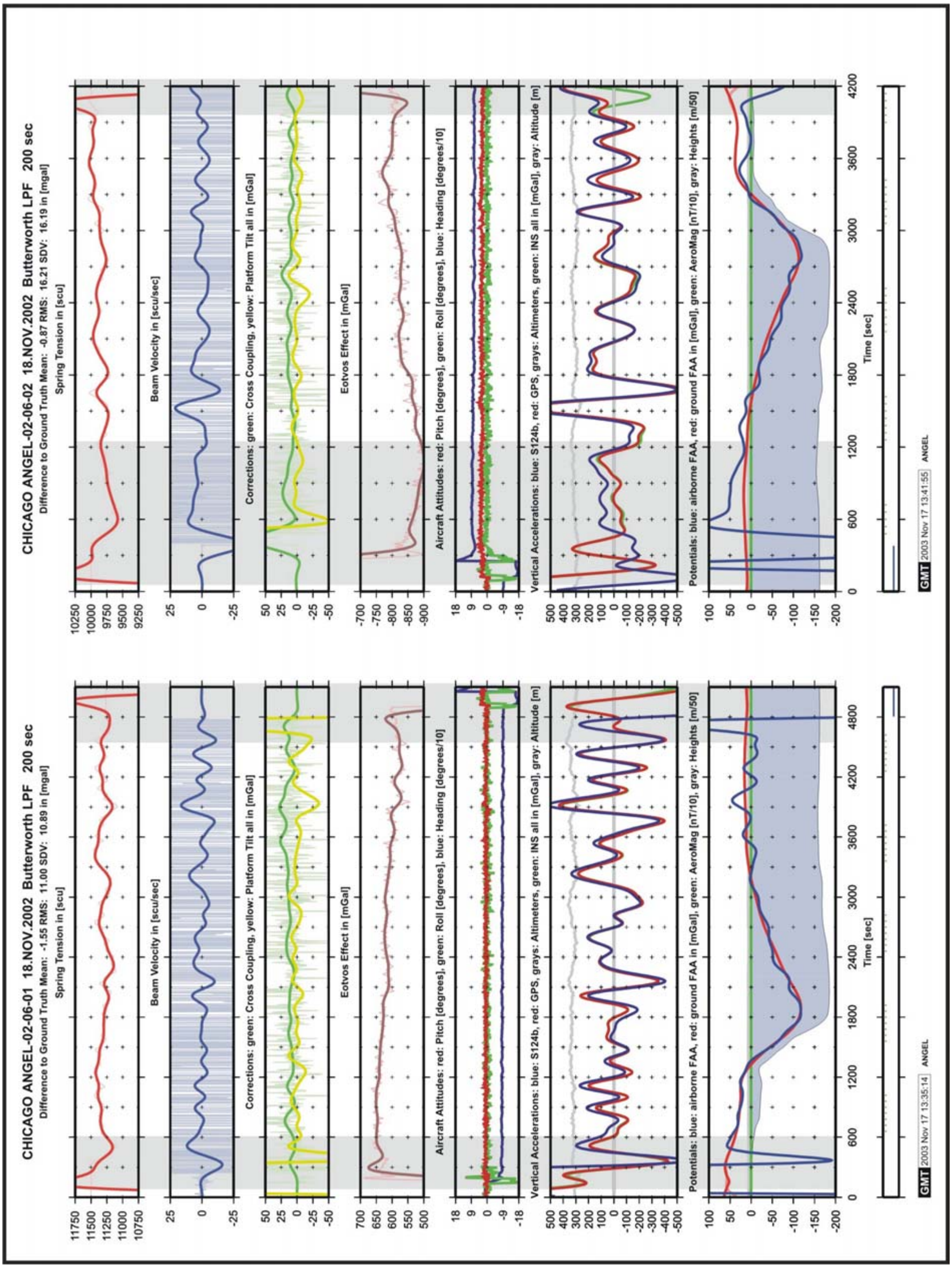

Figure 8.12: Profile data of survey flight ANGEL-02-06.

8.7 Flight ANGEL-02-07

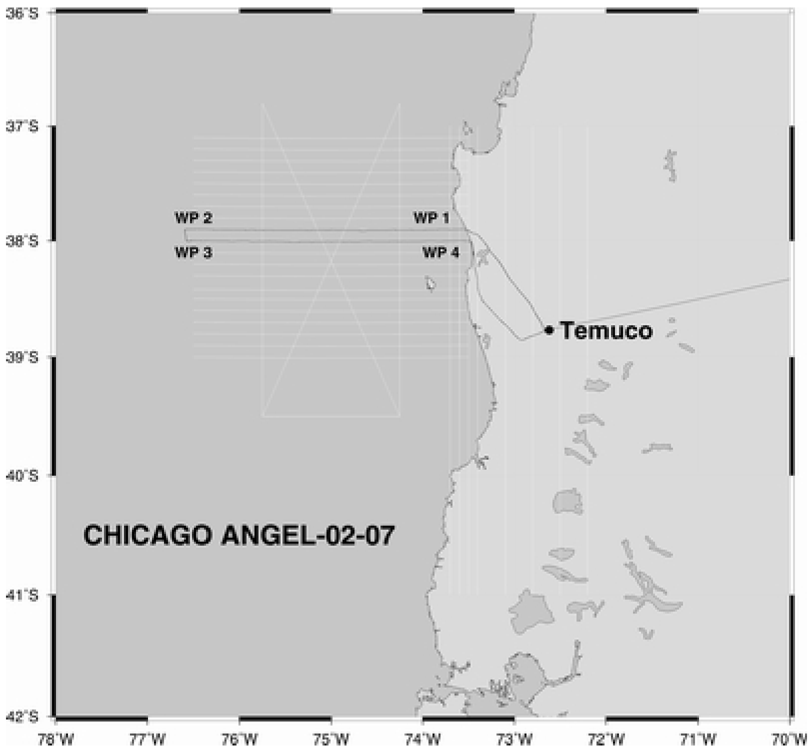

Figure 8.13: Flight path of survey flight ANGEL-02-07.

During flight ANGEL-02-07 (Figure 8.13) weather conditions were as favorable as for most of the other flights. Especially about 80 km off the coastline some air turbulences occurred which left their imprints in flight and data quality. These turbulences went along with sudden deviations in height that decreased the gravity data quality at about profile second 2000 in profile ANGEL-02-07-01 and observation second 2600 in profile ANGEL-02-07-02 (Figure 8.14). These incidents clearly show how that sudden changes in flight altitude still trigger errors in the LaCoste & Romberg instrument. This holds true especially in cases when tilt offsets within the meter occur, meaning that the actual sensor horizontation was not parallel to the platform orientation, resulting in a loss of sensitivity and an increased inertia. Then, strong vertical and side motion impacts produce larger errors and recovering of the meter is longer than with optimized horizontation alignment between internal sensor and platform. The maintenance check at LaCoste & Romberg showed that such a misalignment had to be corrected for. We still have to keep in mind when discussing these effects, that especially for this flight, the general vertical accelerations of the aircraft are about a factor of ten higher in the low-pass filtered state than with flights using an autopilot system. Therefore, even small errors or misadjustments in the gravity meter might produce significant effects on the profile. All airborne profiles are filtered with the minimum low-pass filter window, so with an only slightly longer window, most of these effects will vanish.

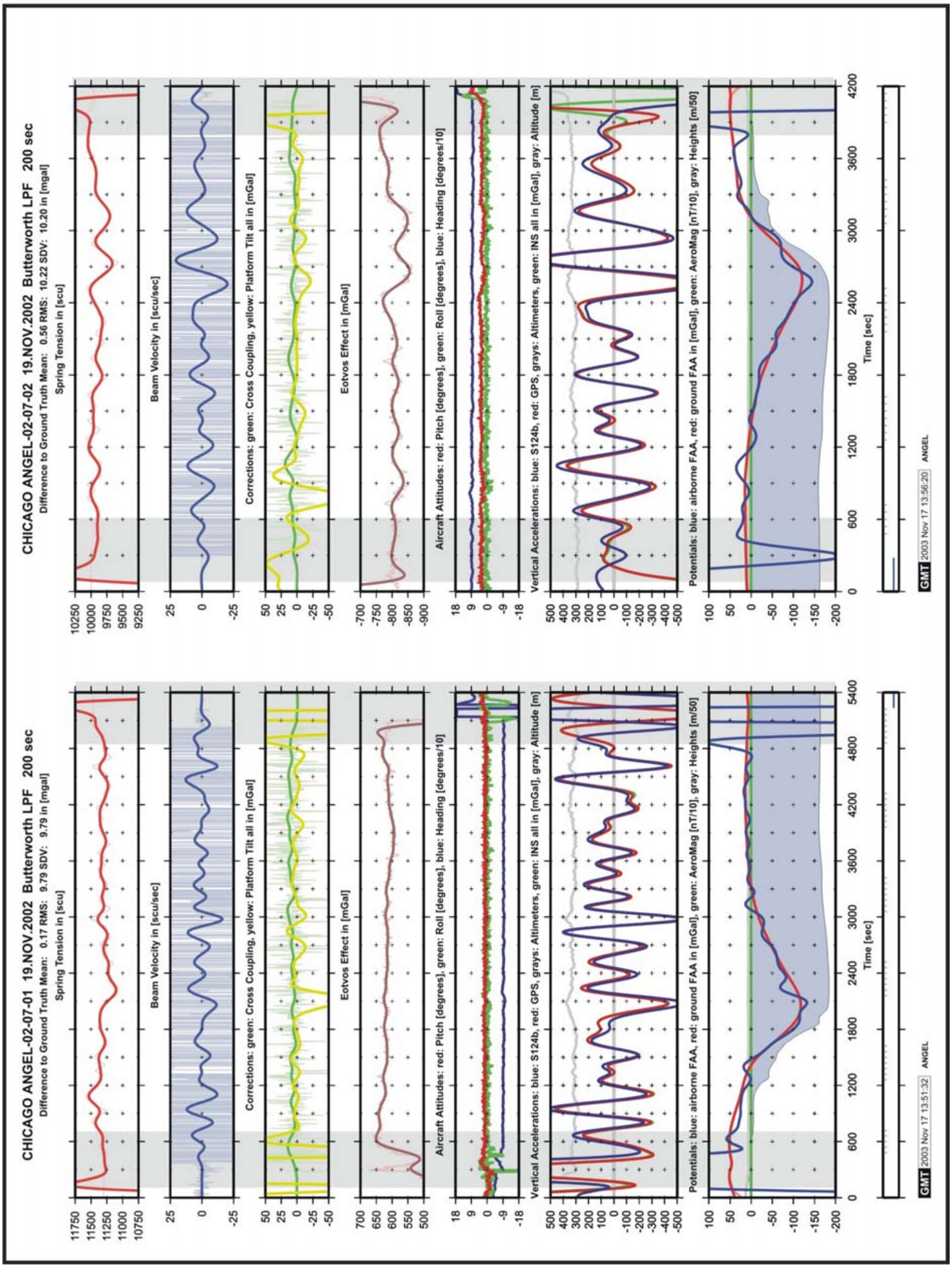

Figure 8.14: Profile data of survey flight ANGEL-02-07.

8.8 Flight ANGEL-02-08

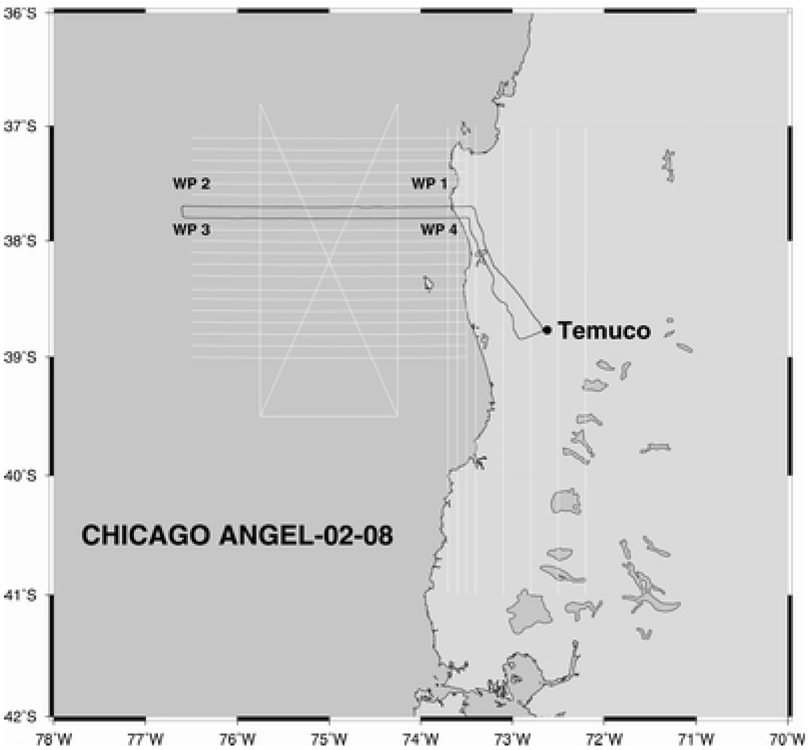

Figure 8.15: Flight path of survey flight ANGEL-02-08.

Flight ANGEL-02-08 (Figure 8.15) has an overall good quality in the resulting data. Due to a lack of a sufficiently high number of satellites for kinematic GPS processing, data gaps occur in the second profile, ANGEL-02-08-02 (Figure 8.16). Comparing this flight to the last one discussed, ANGEL-02-07, the vertical acceleration range specifically for profile ANGEL-02-08-02 is about half the scale of the former one. This directly leads to an increased quality of the resulting data.

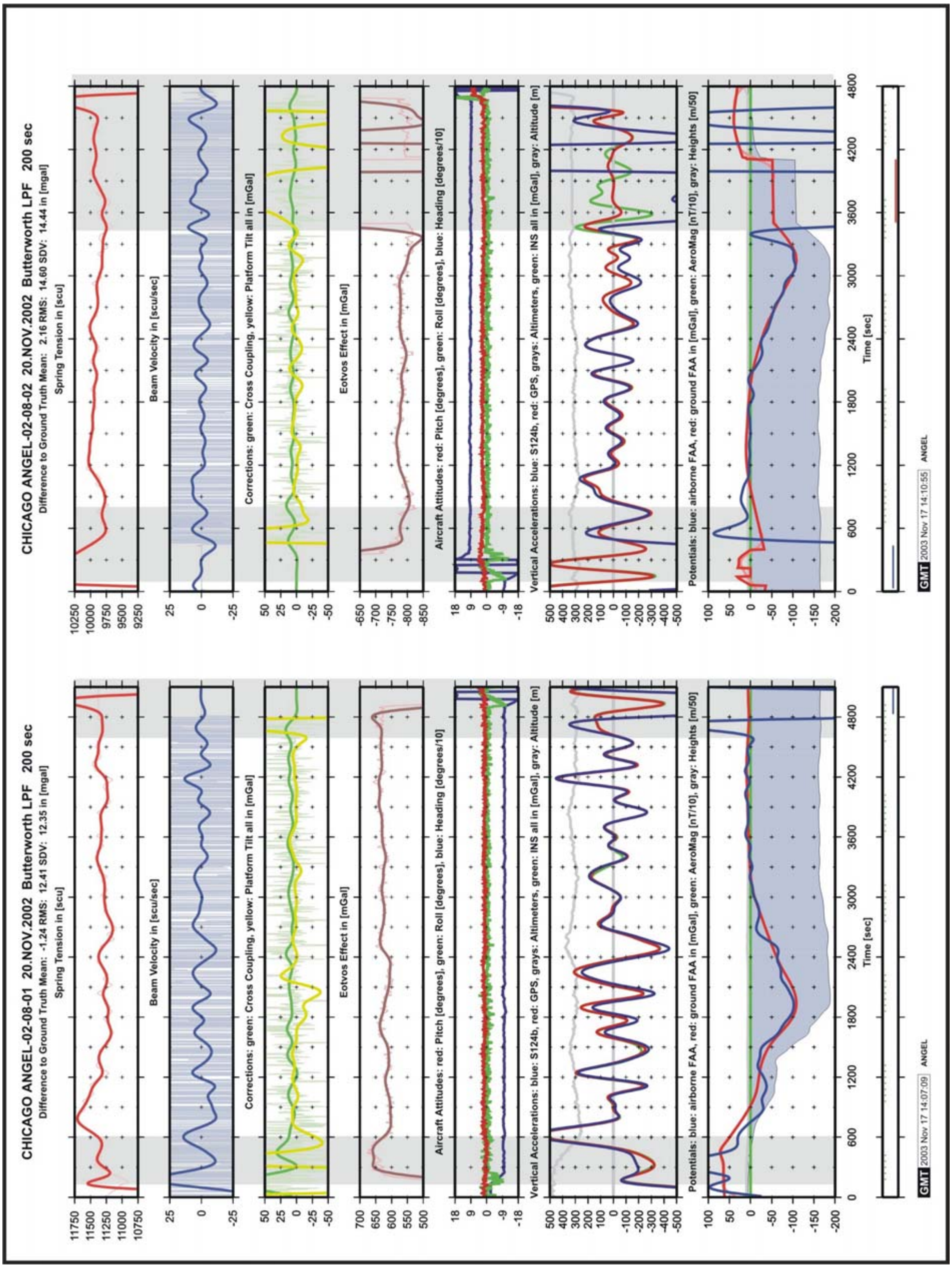

Figure 8.16: Profile data of survey flight ANGEL-02-08.

8.9 Flight ANGEL-02-09

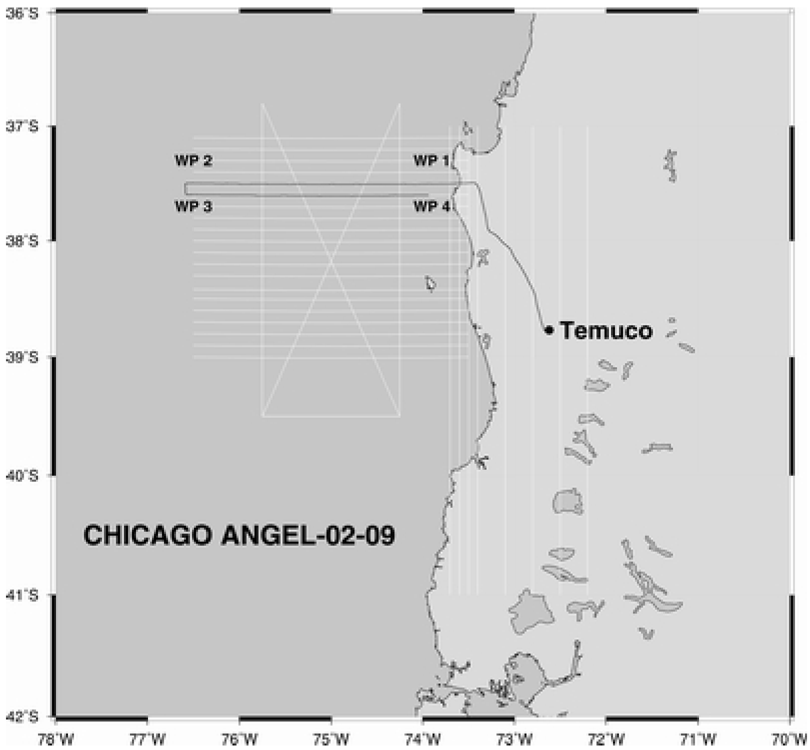

Figure 8.17: Flight path of survey flight ANGEL-02-09.

Flight ANGEL-02-09 (Figure 8.17) shows no effects that have not yet been discussed. The general data quality as good as can be expected for flights without autopilot systems and all major bathymetric structures are revealed in the profiles (Figure 8.18).

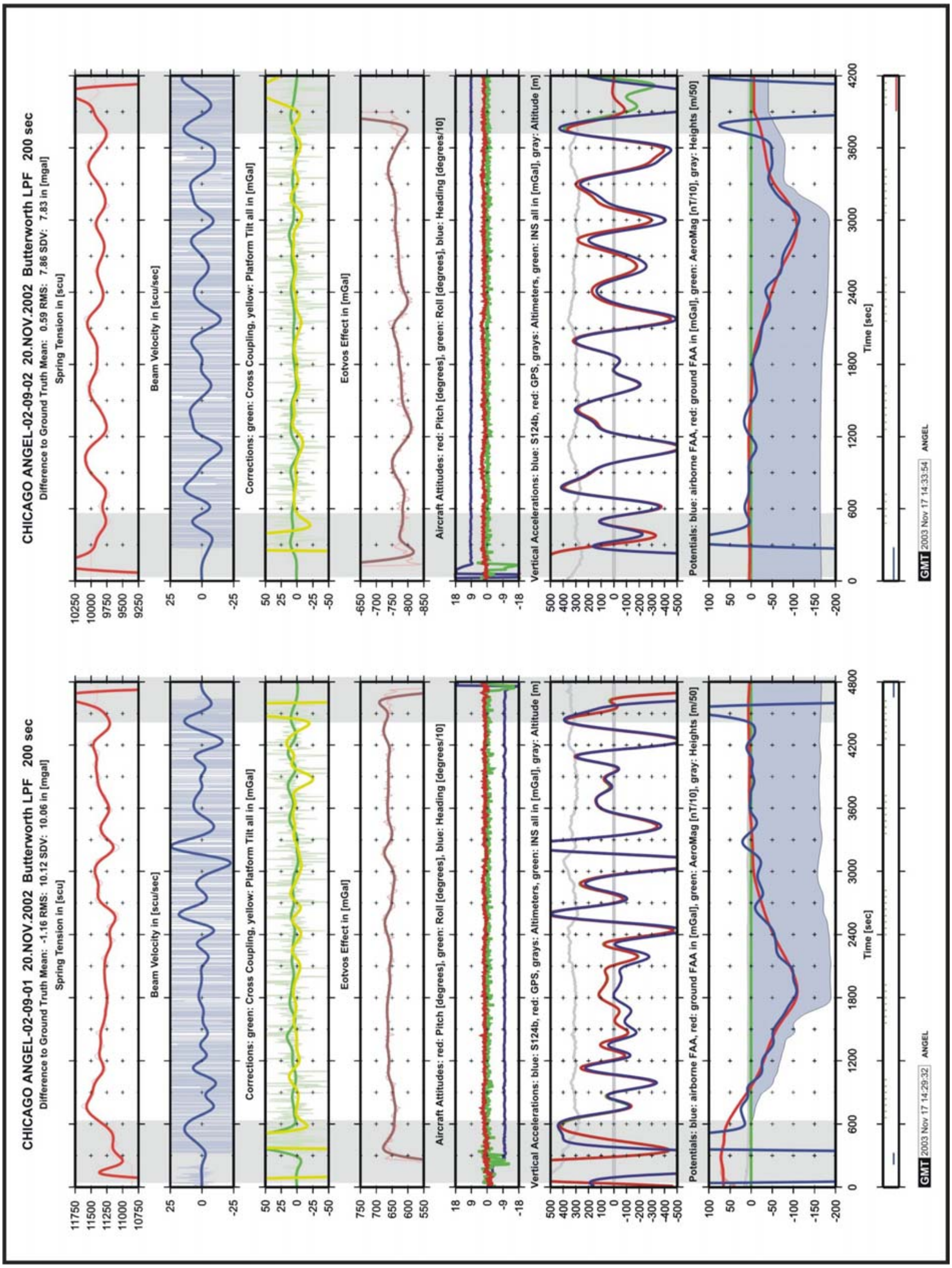

Figure 8.18: Profile data of survey flight ANGEL-02-09.

8.10 Flight ANGEL-02-10

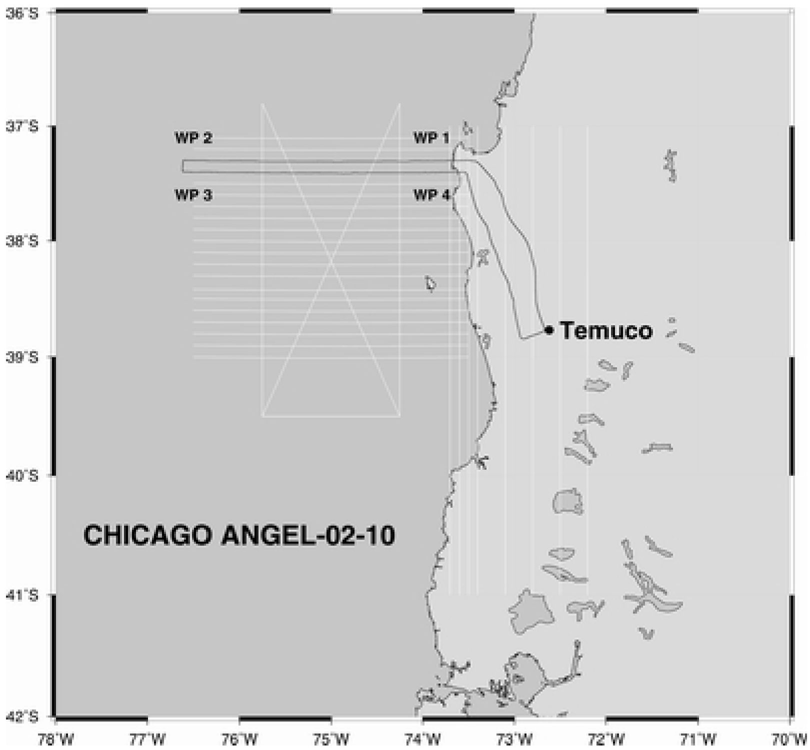

Figure 8.19: Flight path of survey flight ANGEL-02-10.

Due to some air turbulence along the coast the first part of flight ANGEL-02-10 (Figure 8.19) was disturbed and could not be used as part of the resulting survey profile (Figure 8.20). A wrong pre-setting of the gravity meter spring tension for the start of the second profile, ANGEL-02-10-02, lead to a similar problem. Otherwise, the data quality specifically for the first profile, ANGEL-02-10-01, was very good.

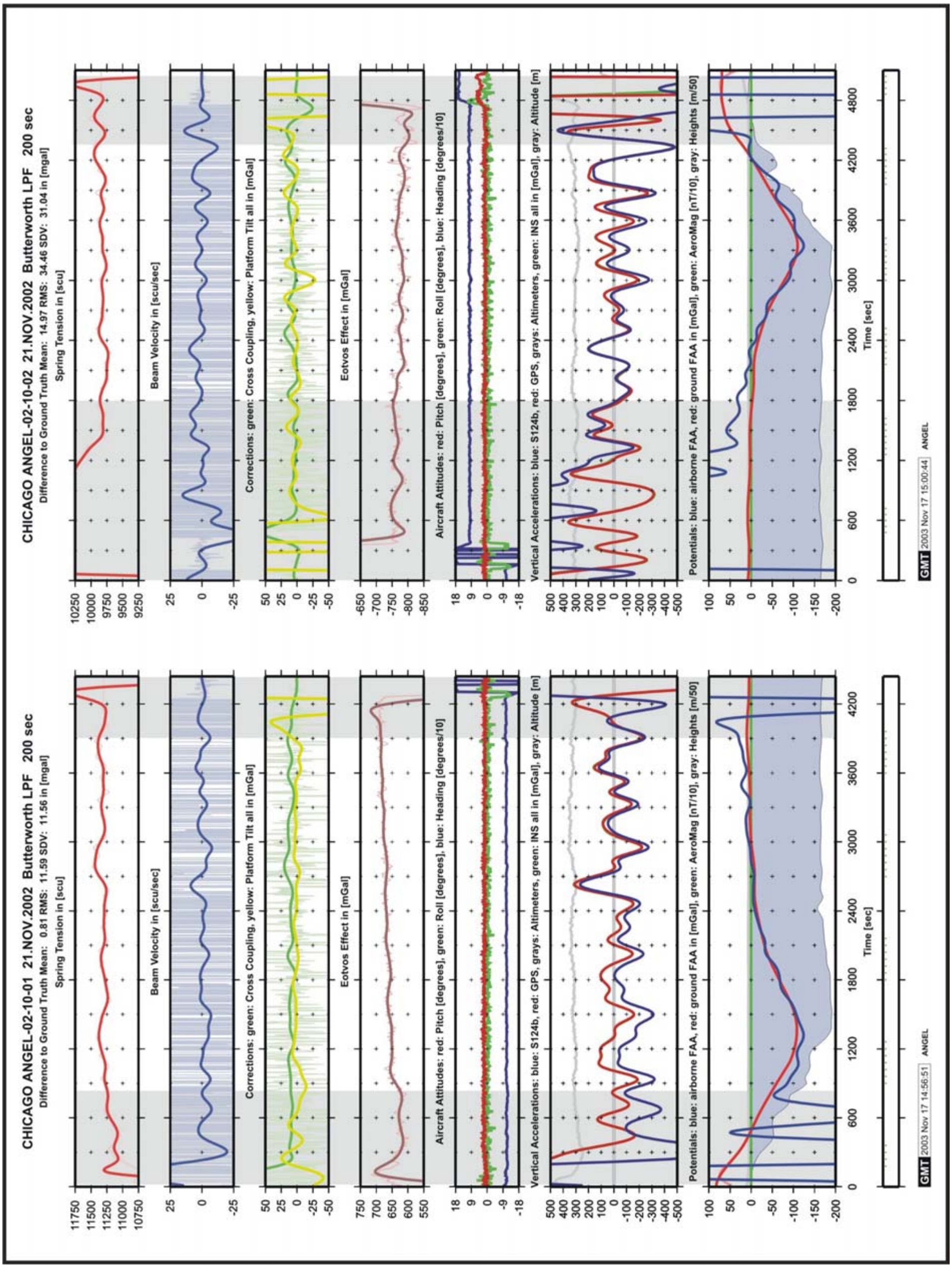

Figure 8.20: Profile data of survey flight ANGEL-02-10.

8.11 Flight ANGEL-02-11

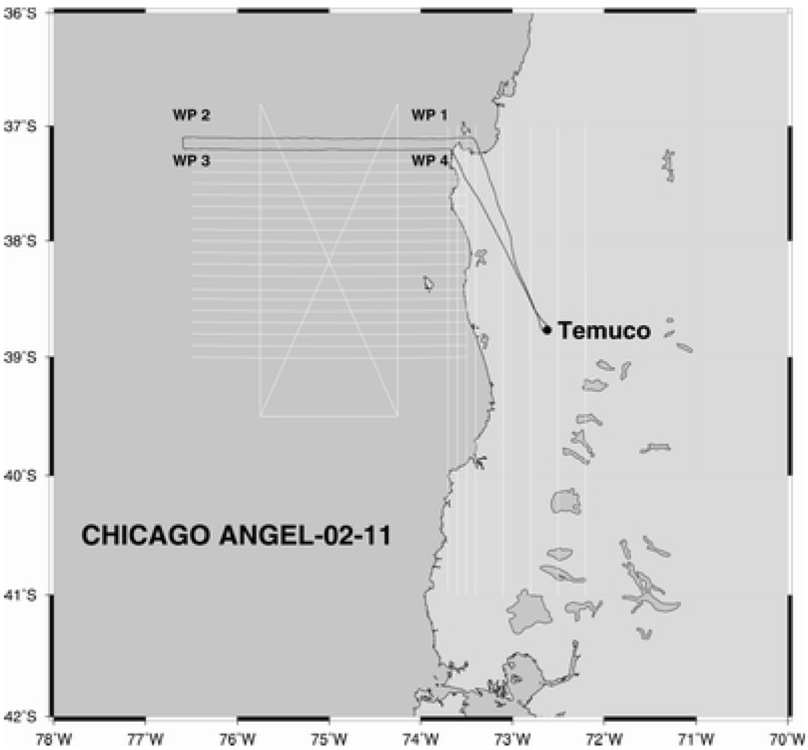

Figure 8.21: Flight path of survey flight ANGEL-02-11.

Flight ANGEL-02-11 (Figure 8.21) is the last of the EW-oriented offshore survey flights. The general data quality is good, although some high aircraft acceleration deteriorate the results slightly at the begin of profile ANGEL-02-11-01 (Figure 8.22).

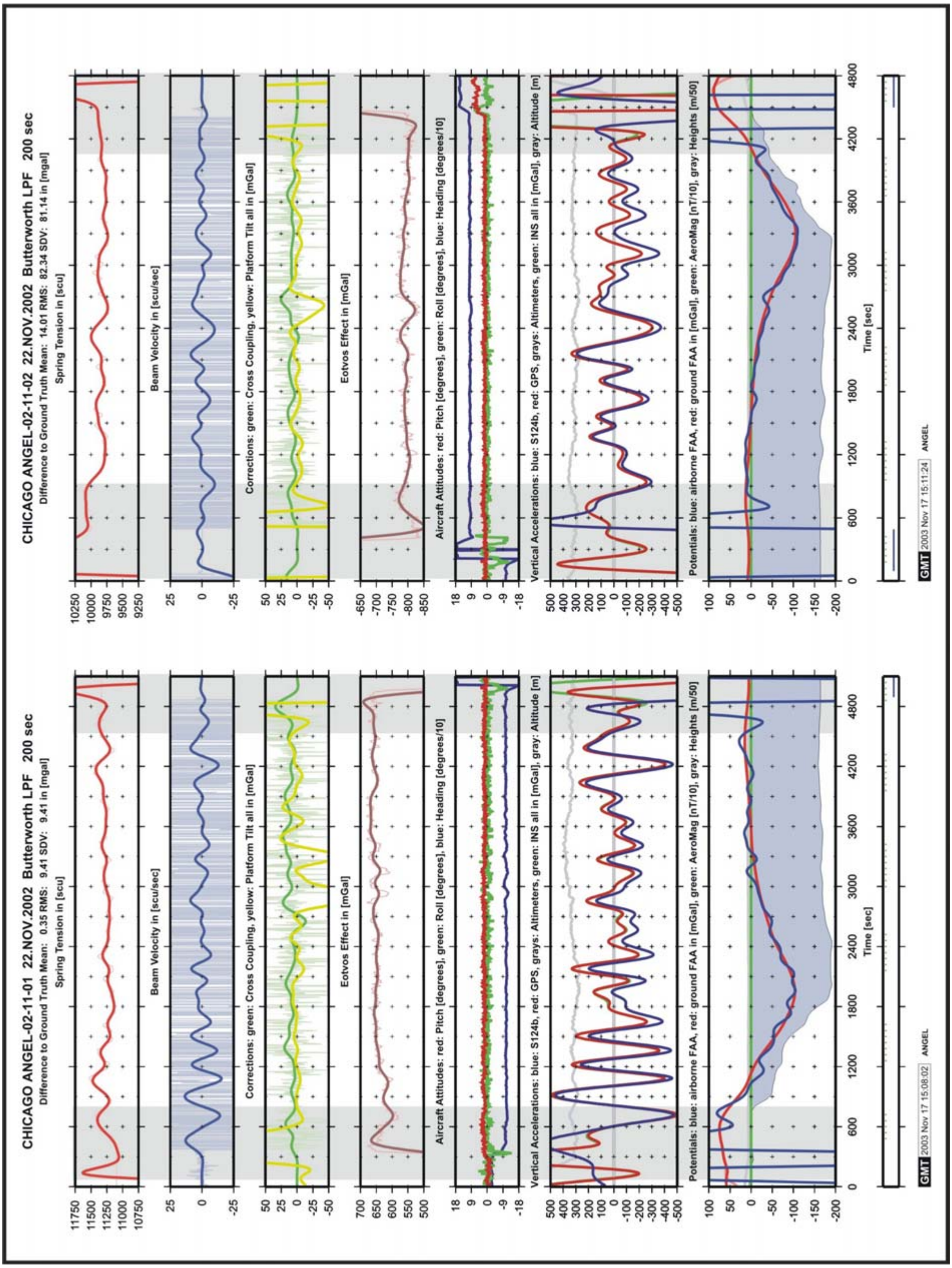

Figure 8.22: Profile data of survey flight ANGEL-02-11.

8.12 Flight ANGEL-02-12

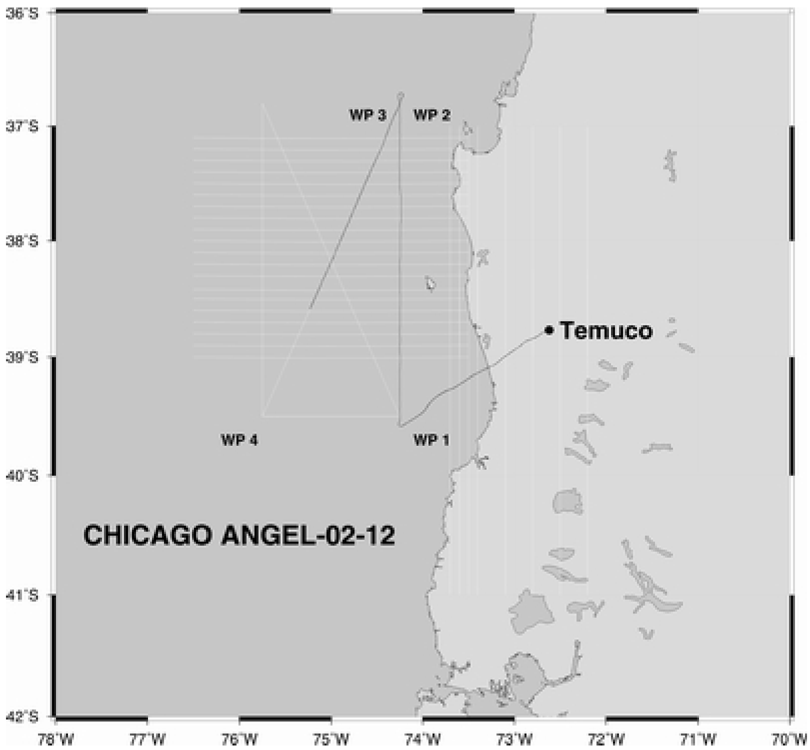

Figure 8.23: Flight path of survey flight ANGEL-02-12.

Flight ANGEL-02-12 was the first flight to cross the EW-oriented offshore flights (Figure 8.23). Unfortunately, Trimble Total Control could not compute kinematic GPS results for the last part of the flight (Figure 8.24). This part could be recovered by the KSG-Soft program but is not shown here. Most of the other offshore profiles were flown with or against the general wind direction, on this flight a moderate wind was perpendicular to the flight direction, which made it more difficult for the pilots to maintain a stable straight and level flight. Therefore, these flights were conducted at the end of the offshore part, when the pilots had developed a good feeling for survey conditions required. A leveling and crossing point analysis has not been carried out so far but will be done in preparation to publish these results in a reviewed journal.

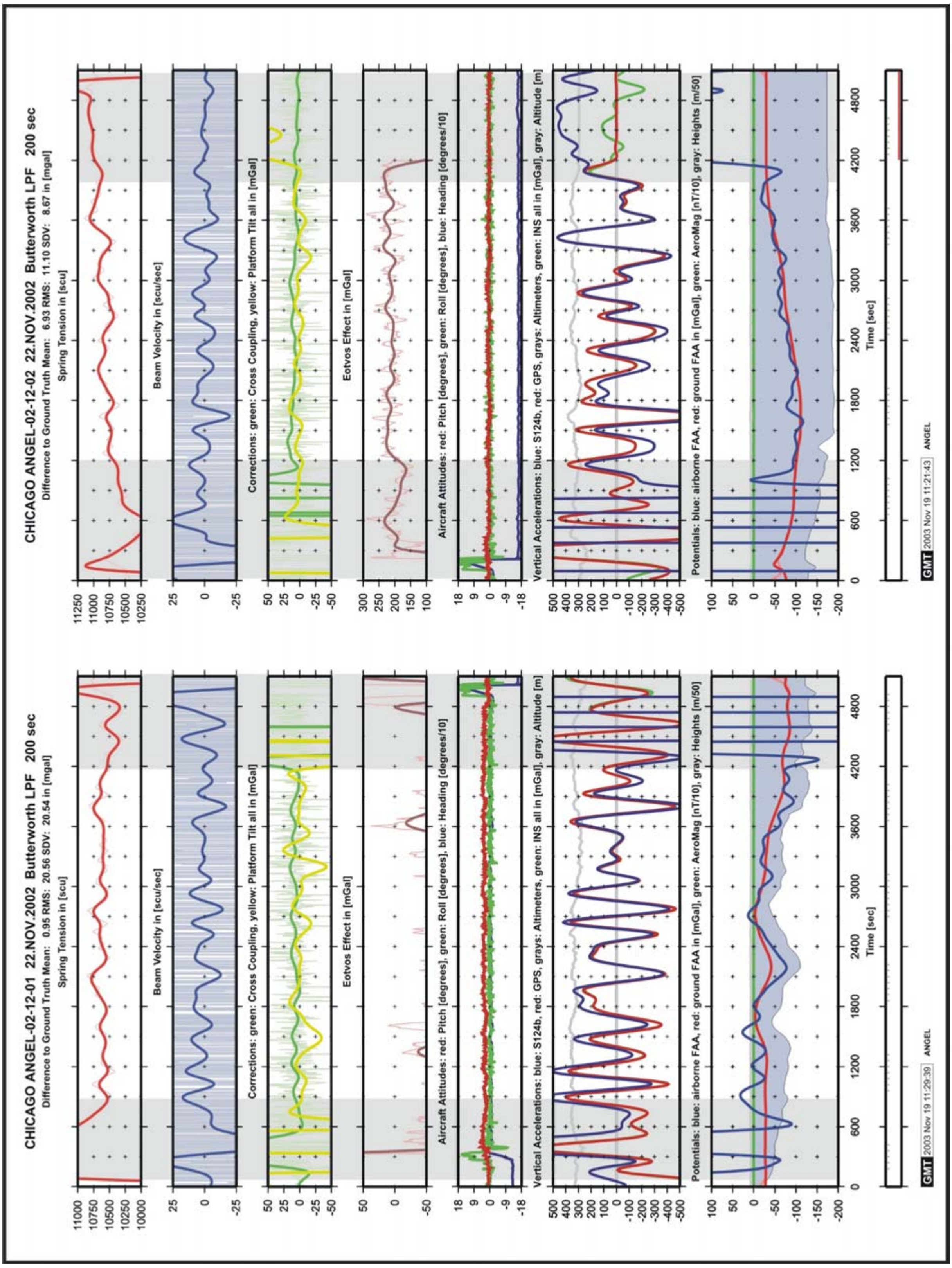

Figure 8.24: Profile data of survey flight ANGEL-02-12.

8.13 Flight ANGEL-02-13

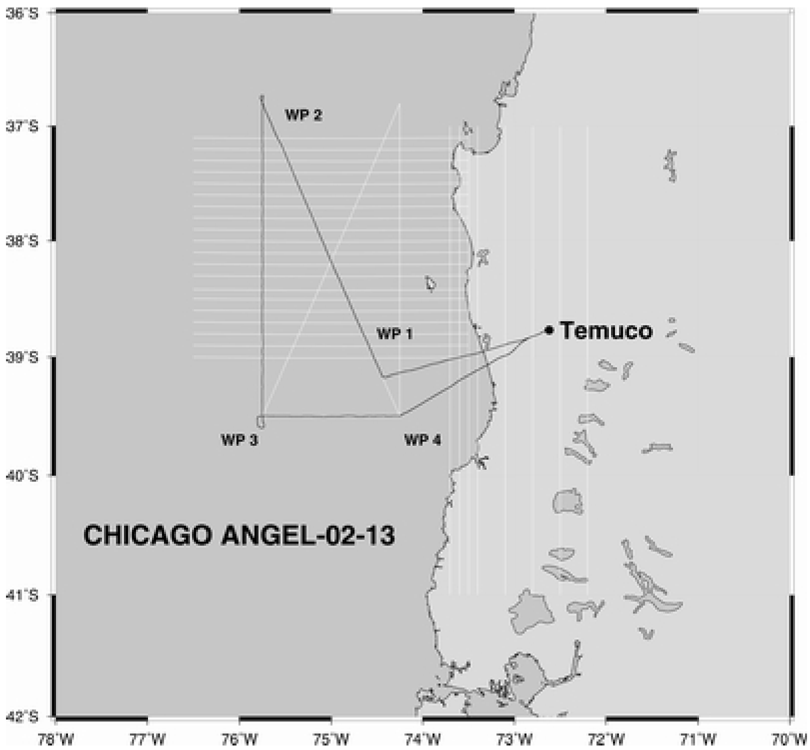

Figure 8.25: Flight path of survey flight ANGEL-02-13.

The last flight of the offshore survey and the longest flight of the complete survey (Figure 8.25), ANGEL-02-12, could be processed on all three profiles without major difficulties. Profile ANGEL-02-12-01 is just once disturbed by a sudden change in the flight altitude and suffers from small gap in the kinematic GPS data close to the end of the profile (Figure 8.26). Profile ANGEL-02-12-02 is in total of good quality. Profile ANGEL-02-12-03 (Figure 8.27) can be used as a good example to estimate the general errors on the gravity data induced by large aircraft motion disturbances. The mean rms error here with the full resolution of 6.5 km half-wavelength on the profile is about 15 mGal.

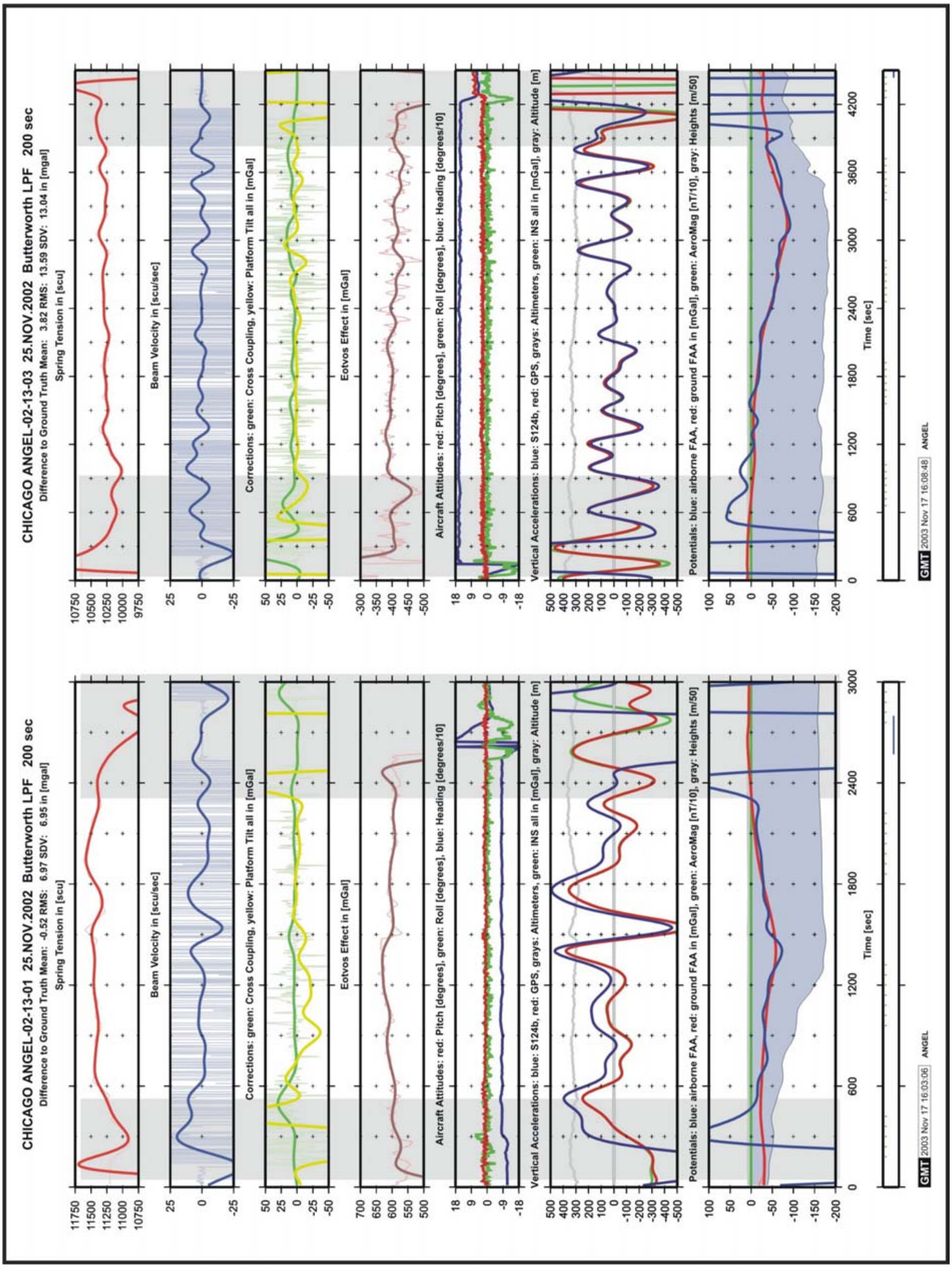

Figure 8.26: Profile data of survey flight ANGEL-02-13.

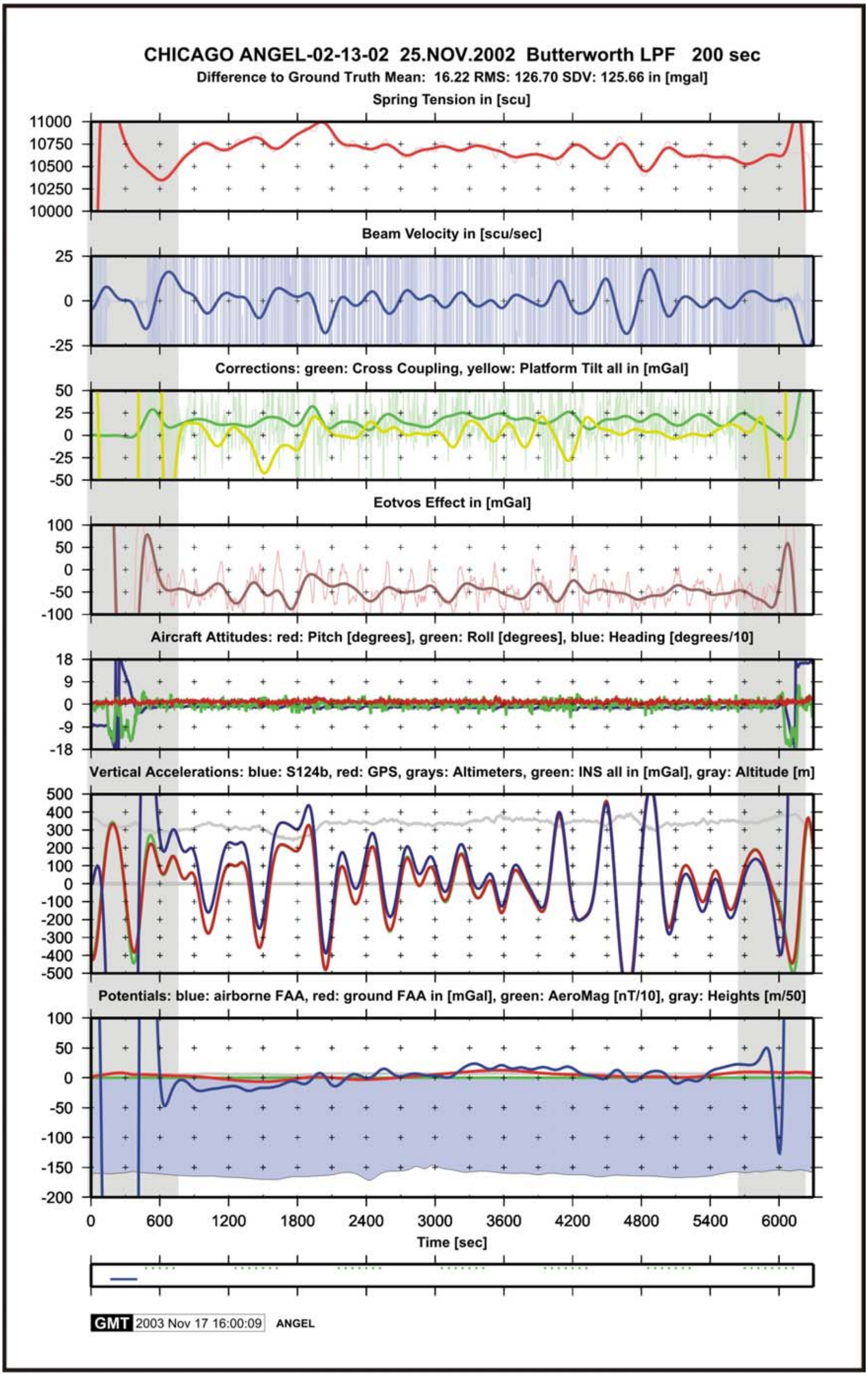

Figure 8.27: Profile data of survey flight ANGEL-02-13.

9 Onshore survey flight results

9.1 Introduction

The second part of the CHICAGO survey concentrated on near-shore to offshore profiles, flown in NS-direction. The profiles were mostly flown at 7000 ft above sea level close to the coast and over the coastal cordillera. Only the last, easternmost flight was flown at 10000 ft, due to the rugged terrain dominated by the volcanoes. For political reasons, it was not possible to fly closer to the Argentinean-Chilean border than 50 km using an aircraft of the Chilean Air Force; this defined our easternmost profile coordinates. In the future, closer approaches to the border or even crossings are possible if an Argentinean military officer is on board the Chilean military aircraft and all necessary diplomatic negotiations have been made well beforehand.

From other aerogravimetric survey flights over land (i.e. MEXAGE, Mexican Aero-Geophysical Experiment) we expected rougher flight conditions than those over open seawater due to upwelling airstreams etc. Fortunately, this was not the case during our time in Chile. Even over rugged terrain and areas of sudden vegetation changes the air was extraordinary calm. The main reason for this was the missing temperature gradient between ground and air. Both were (in late spring) of roughly the same temperature. Moreover, a stable large meteorological high-pressure system reaching almost as far south as Puerto Montt stabilized flight conditions. Only a few kilometers north of Puerto Montt low clouds and occasional rain occurred. Just on one flight close to Puerto Montt icing conditions on the aircraft developed for a couple of minutes. For the flights offshore, it was good enough to have GPS ground reference stations in Temuco, Puerto Saavedra and Concepcion. For the onshore, NS-directed flights, a GPS base station was set-up at the military part of the airport of Puerto Montt (Figure 2.6). The maintenance of this station for less than one week was the task of a pilot stationed at the military airport site in Puerto Montt. Due to a technical problem and the lack of communication only a few hours of GPS data was recorded at Puerto Montt. Therefore, all kinematic DGPS aircraft positions were computed using the GPS base at Temuco and the front antenna of the aircraft. Consequently, the GPS computing was identical to the one for the offshore flights.

Normally, the aerogravimetric profile should be as long as possible and as undisturbed as possible to maintain best efficiency and data quality. For the onshore flight within CHICAGO we were not able to stick to the optimum flight patterns. A compromise between flight endurance, flight safety and measurement performance had to be found. We already had installed an extra fuel tank that enabled us to stay airborne for more than four hours. We therefore were forced to break one of the planned long NS profiles into two. Temuco was about at the mid-latitude of the survey area. Hence, the first profile was split into two parts with a certain overlap to account for filter onsets, navigation adjustments and climb rates. When in the subsequent pages the results of these survey flights are discussed, this is mainly based on the comparison to land elevation and gravity ground truth data. The topography was extracted along the profile using the ETOPO'2 data set as already done for the offshore flights. As for the marine part of the topographic data set, errors in location and missing structures might occur.

The ground truth gravity data was gridded and then extracted from the grid using SFB267 data as well as data from the University of Sao Paulo, namely from the working group of Prof. Denizar Blitzkow (Figures 9.1 and 9.2). As for the offshore flights, the relative measurements of the LaCoste & Romberg gravity meter system had to be fixed to a regional gravity network. This was done by a transfer measurement using a LaCoste & Romberg G-meter between a known absolute gravity point at the site of the civilian part of the airport in

Temuco and the site of the Twin Otter aircraft at the military part of the same airport. Andres Tassara carried out this transfer measurement (Table 9.1). Although this measurement was counter checked twice, we had to apply a negative offset of 150 mGal to fit the free-air gravity derived from the airborne survey to the ground truth measurements. The same applied for the marine part of the survey with the same offset. Until now, we only can speculate about the source of the difference.

Absolute gravity point at Temuco airport:	980030.65 mGal
Relative G-meter reading at Temuco airport absolute gravity point:	3615.08 mGal
Relative G-meter reading at Temuco survey aircraft site:	3610.58 mGal
Related absolute gravity at Temuco survey aircraft site:	980026.15 mGal
Base reading of LaCoste & Romberg sensor at Temuco survey aircraft site:	10854.5 mGal

Table 9.1: Tie between LaCoste & Romberg S124b observations and local absolute gravity

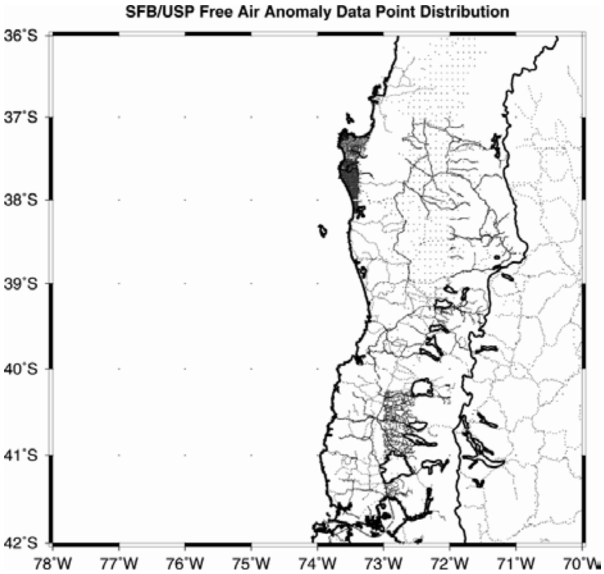

Figure 9.1: Distribution of the land based free-air anomaly data points. 11950 points were supplied by the SFB-267 database and 880 points were extracted from the gravity database of the University of Sao Paulo.

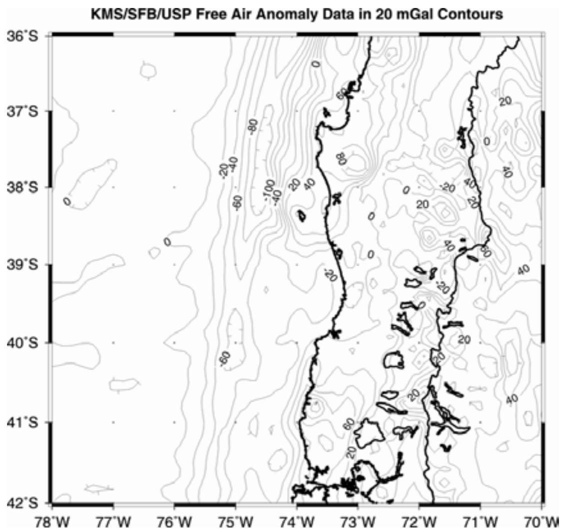

Figure 9.2: Free-air anomaly map based on KMS'99 offshore free-air data and the land based data shown in Figure 9.1.

9.2 Flight ANGEL-02-14

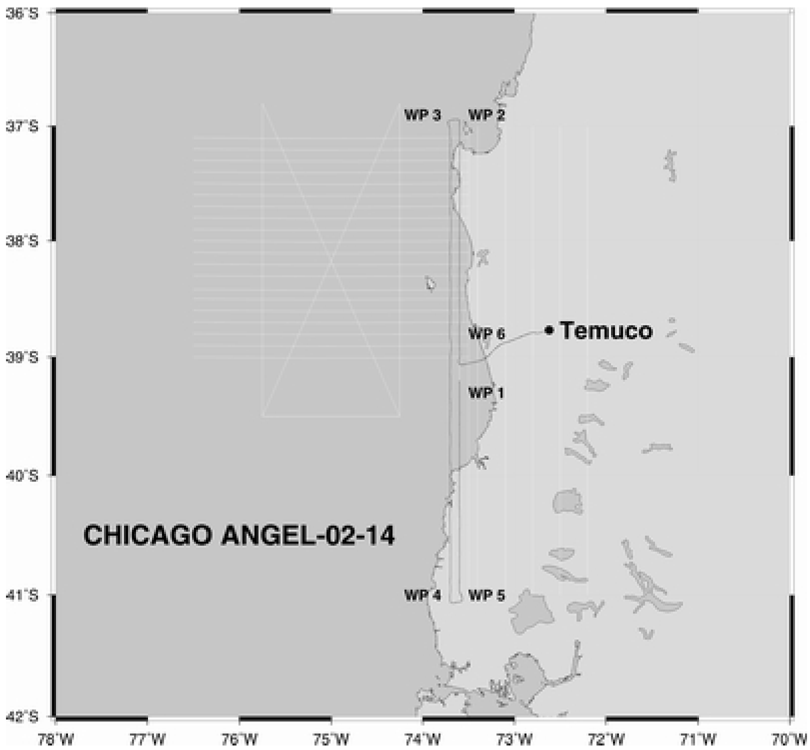

Figure 9.3: Flight path of survey flight ANGEL-02-14.

As all other subsequent flights over land, the flights lines of ANGEL-02-14 are broken into three profiles (Figure 9.3). The first large NS-directed line is subdivided into two parts. The first waypoint is about 50 km south of the midpoint of the complete line. After the turn in the north the second profile runs for the whole length towards the south. The last waypoint of the profile towards north is then located about 60 km north of the first waypoint.

Flight ANGEL-01-14 partly crosses land and sea as the coastline varies (Figure 9.3). The profile altitude was 7000 ft; the flight conditions were calm except for the southernmost part. Profile ANGEL-02-14-01 clearly shows much higher correlation and also amplitude variation when compared to the bathymetry and topography data than the smooth ground truth data (Figure 9.4). The ground truth data close to the coast consists mainly of interpolated free-air data derived from KMS'99 altimetry and patchy land based gravity data along the coast which were interpolated to a 10' x 10' grid for the offshore region and a 5' x 5' grid for the onshore region. Therefore, we cannot expect to see any details in the ground truth data but just the general trend. Profile ANGEL-02-14-02 follows the long wavelength trend nicely but also shows a good correlation to the hilly topography in the southernmost part. The turn towards the north lead through clouds, icing conditions and some turbulence, which translate directly into some gravity meter disturbances. Therefore, a large part of the start of the last profile had to be omitted. Due to a lack of a sufficient number of GPS satellites the last part of profile ANGEL-02-14-03 could not be adequately processed.

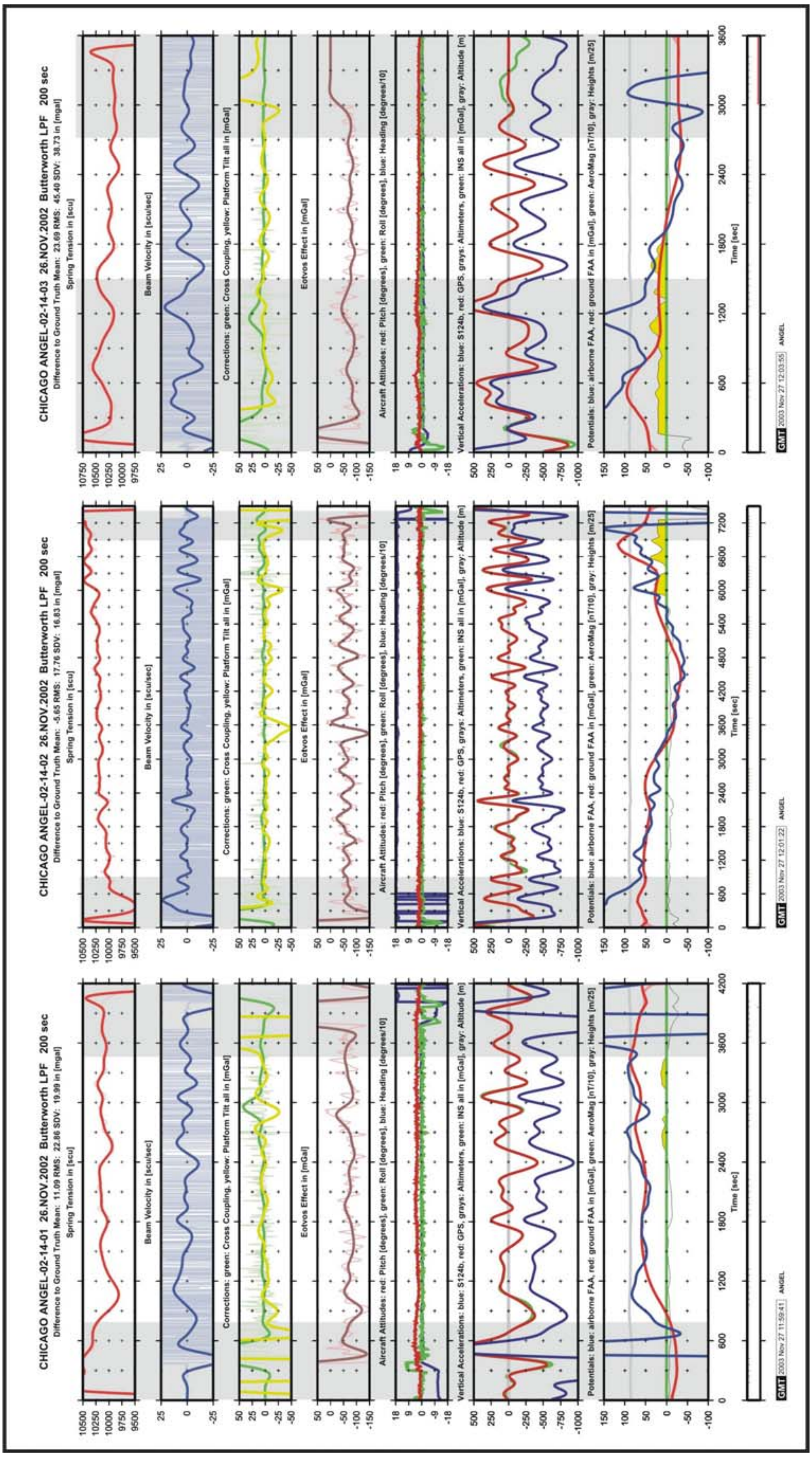

Figure 9.4: Profile data of survey flight ANGEL-02-14.

9.3 Flight ANGEL-02-15

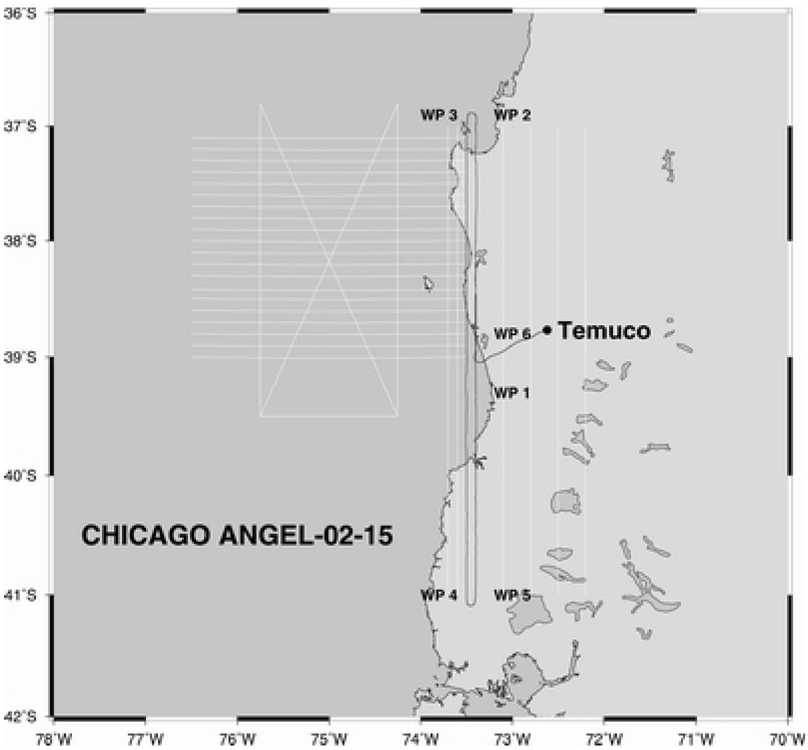

Figure 9.5: Flight path of survey flight ANGEL-02-15.

Survey flight ANGEL-02-15 (Figure 9.5) shows basically very much the same long wavelength features as the previous one: a gravity low in the area where coastline retreats eastwards (Figure 9.6). As already discussed, the available ground truth data, gridded based on a cell size of 5’ x 5’, will only give general trends and will under-represent topographic features. The airborne gravity data clearly follows the long wavelength trend but also shows significant anomalies related to topographic expressions. This results in an RMS difference of about 20 mGal as already observed in the earlier flight. The flight level was 7000 ft as in the previous one. The operator log states mostly quiet flight conditions except for the southernmost part.

The quality of the flights ANGEL-02-14 and ANGEL-02-15 is a bit of surprise because normally along the coastline the strongest winds occur more or less perpendicular to it. In our case, we only suffered from some clouds in the vicinity of Puerto Montt.

The data sequence from 600 to 900 seconds in profile ANGEL-02-15-01 and the data sequence between 3600 and 4000 seconds covers more or less the same area and are in good accordance respecting the rough topography and the slight longitudinal offset in profiling.

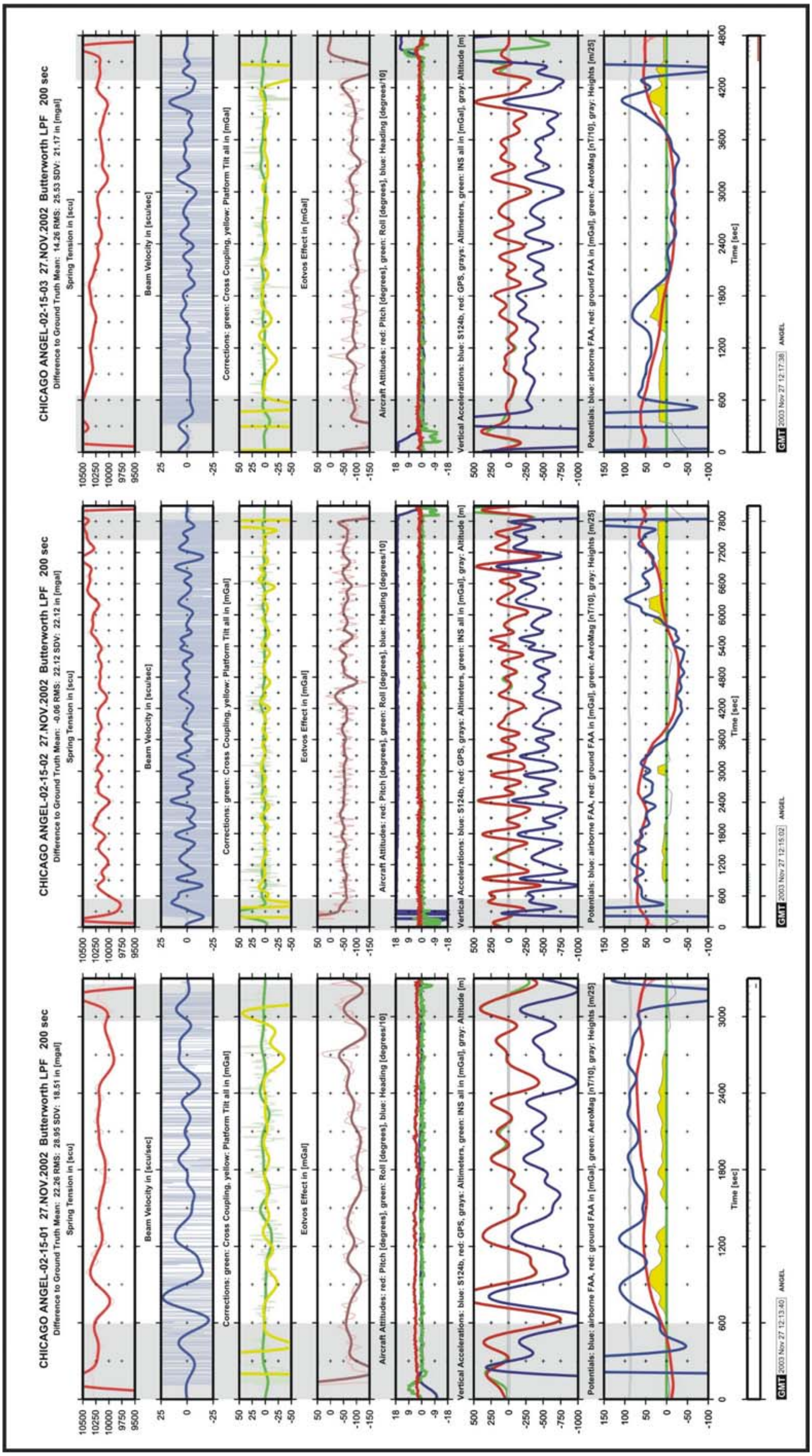

Figure 9.6: Profile data of survey flight ANGEL-02-15.

9.3 Flight ANGEL-02-16

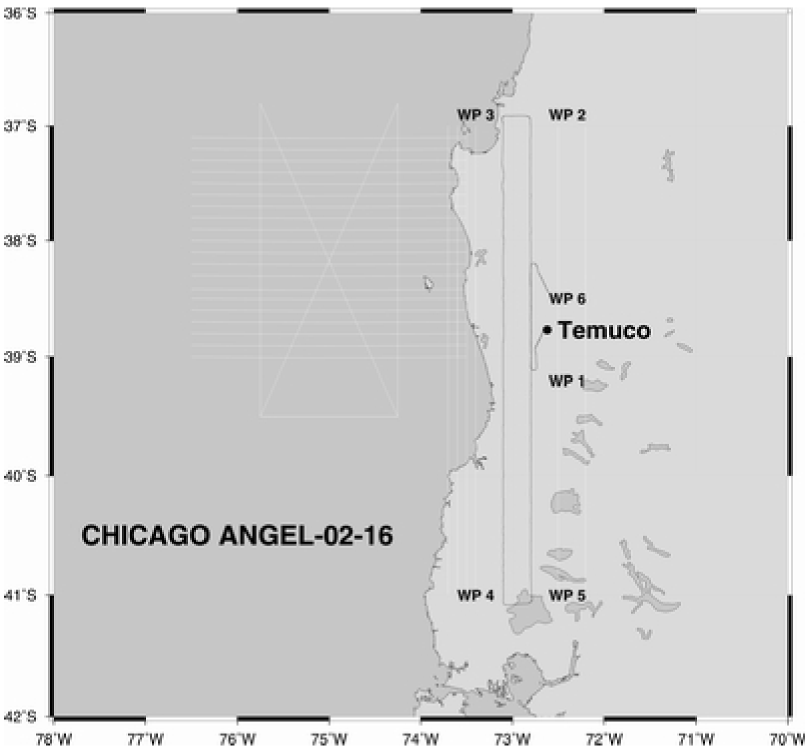

Figure 9.7: Flight path of survey flight ANGEL-02-16.

Survey flight ANGEL-02-16 is the first flight that is completely flown onshore (Figure 9.7). The profiles of the flight cover large parts of the longitudinal basin that steadily dips down southwards until it is underneath the water level. The basin structure is attached to a gravity low, just topographic features form some positive gravity anomalies (Figure9.8).

As we discussed already briefly in the chapter about the offshore survey lines, also the onshore lines are low-pass filtered with the minimum filter length of 200 seconds, resulting in a geological half wavelength resolution of about 6 km. Any higher filter length would stabilize the airborne results but would also cut-off local anomalies.

As in the first two onshore flights, the coastal cordillera and the mountains around Puerto Montt define the main elevations. Therefore, also flight ANGEL-02-16 was performed at a flight level of 7000 ft. Flight and weather conditions were calm except for some turbulence over the southern mountains north of Puerto Montt.

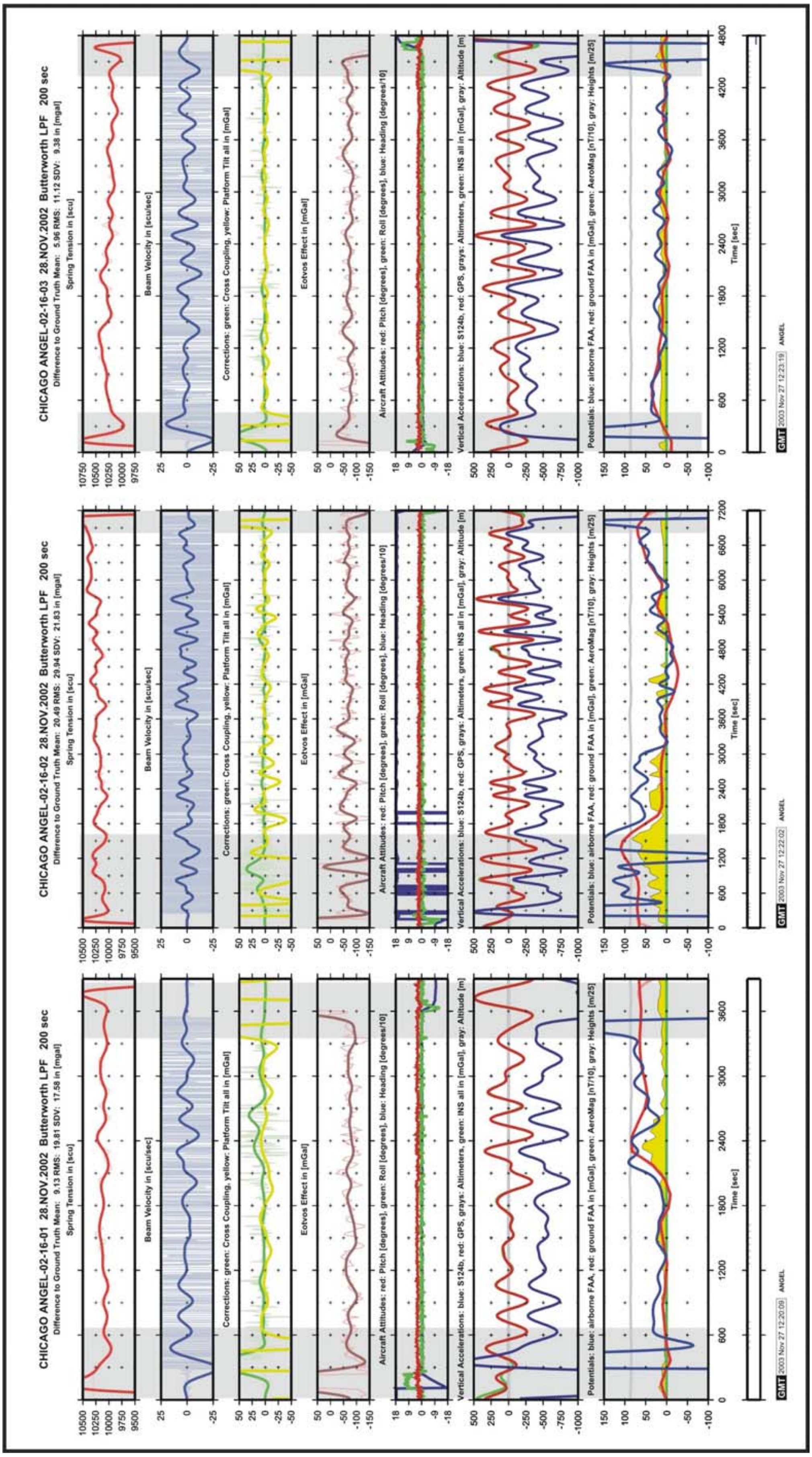

Figure 9.8: Profile data of survey flight ANGEL-02-16.

9.4 Flight ANGEL-02-05

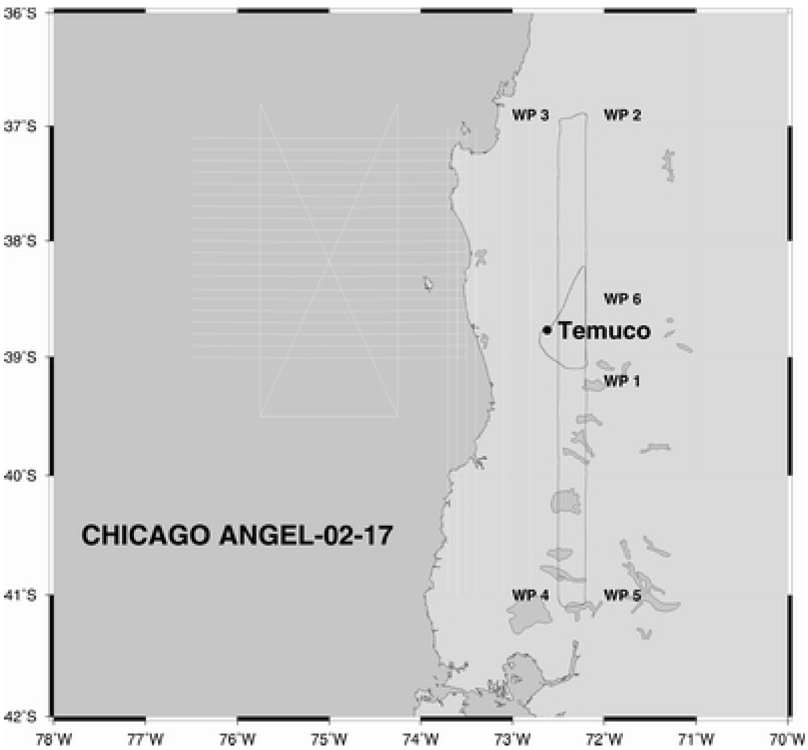

Figure 9.9: Flight path of survey flight ANGEL-02-17.

The last survey flight, ANGEL-02-17 covers the easternmost part of southern Chile (Figure 9.9) and leads directly over some volcanoes that caused small turbulence in the airflow. The flight altitude was 10000 ft, just above the height of the highest volcanoes on the southeastern part of the survey line.

The overall data quality of the flight is good (Figure 9.10).

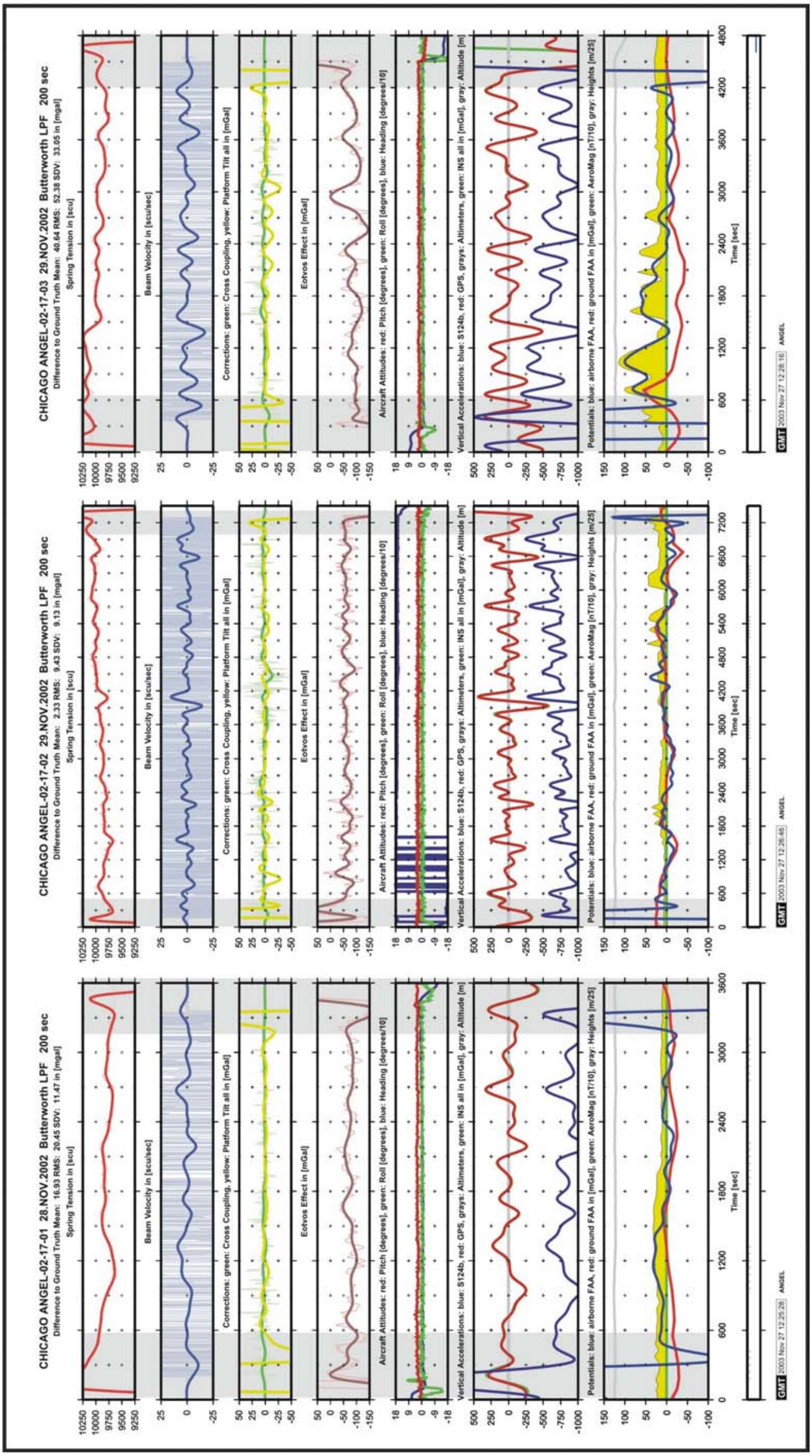

Figure 9.10: Profile data of survey flight ANGEL-02-17.

10 Comparisons

After having discussed the individual flight profiles, some profile and spatial comparisons to available ground truth data are necessary to evaluate the airborne gravity data. Due to the better data overlap and the better ground truth data quality, we constrict the comparisons to the offshore area. Figure 10.1 shows the until lately best gravity map over the region based on the KMS'99 global marine gravity solution with a wavelength resolution of about 20 km [Andersen & Knudsen, 1998]. Figure 10.2 shows the FS Sonne free-air gravity data from the SPOC (Subduktionsprozesse vor Chile) survey with the same wavelength resolution. Both images are very similar except for those parts where the FS Sonne tracks are sparse or do not cover the area. In these cases, interpolation artifacts occur. All grids shown are based on 3' x 3' grid cells. All graphics and grids (of the whole report) are based on GMT utilities [Wessel & Smith, 1991; Smith & Wessel, 1990].

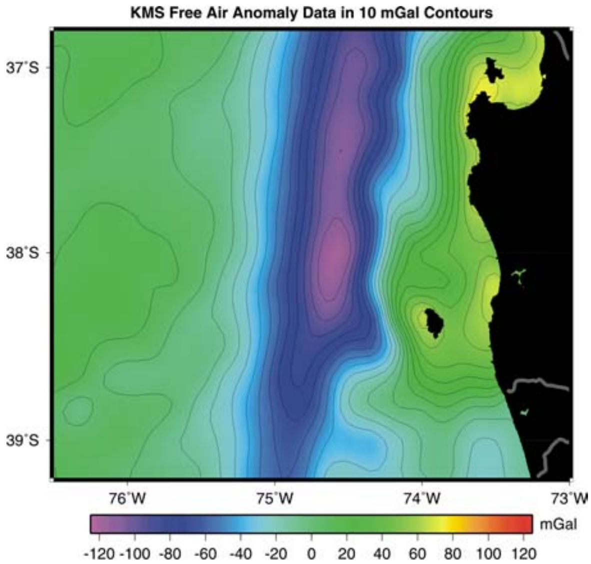

Figure 10.1: Free-air anomalies from the KMS'99 model plotted in 20 mGal contour distances.

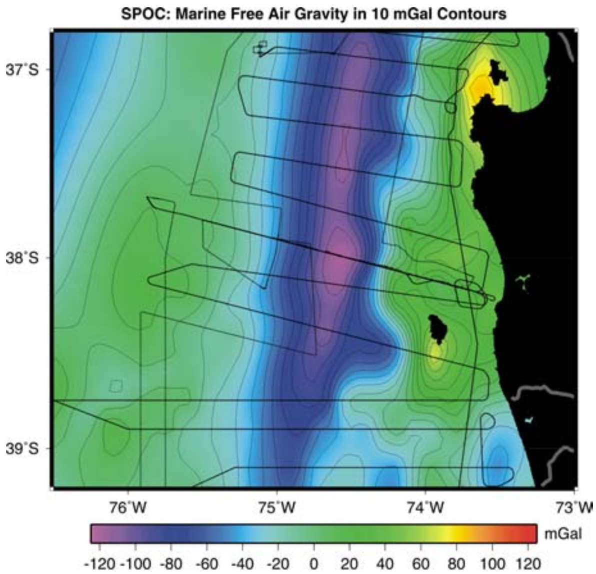

Figure 10.2: SPOC free-air anomalies plotted in 20 mGal contour distances. Marine profiles are given as gray lines in the background.

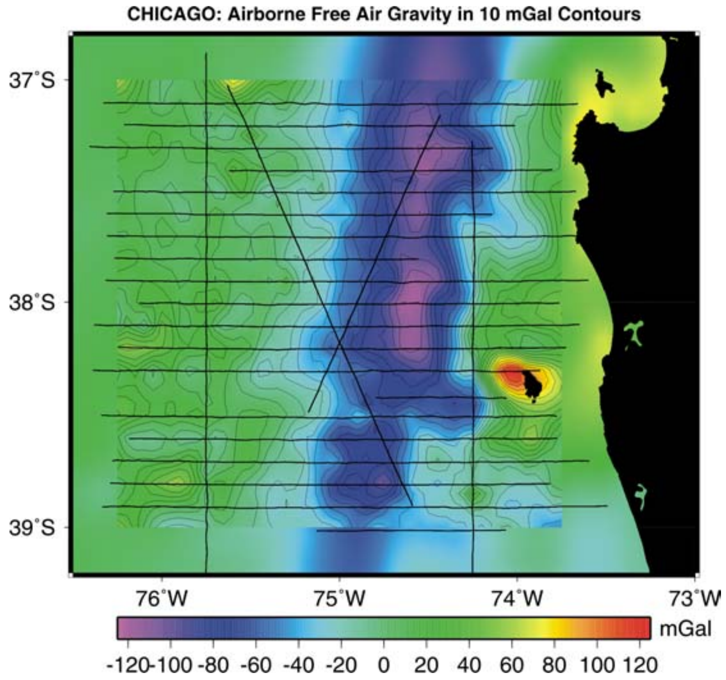

Figure 10.3: CHICAGO free-air anomalies plotted in 20 mGal contour distances. Flight lines are given as gray lines in the background.

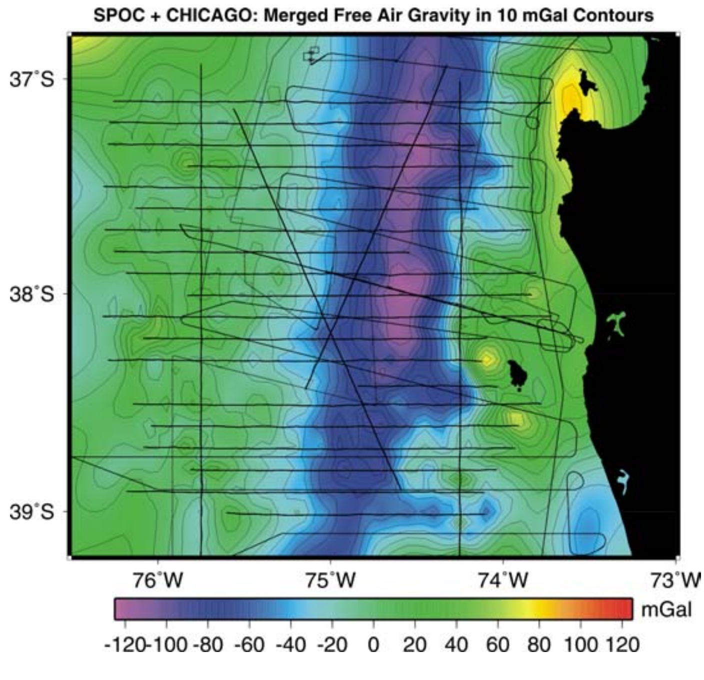

Figure 10.4: CHICAGO and SPOC merged free-air anomalies plotted in 20 mGal contour distances. Airborne and marine profiles are given as gray lines in the background.

Figure 10.3 shows the unleveled free-air anomalies from the CHICAGO survey with a mean wavelength resolution of 6.5 km. All major features observed in Figures 10.1 and 10.2 are resolved where the flight lines cover the area. Additionally, local short-wavelength features occur. Some anomalies such as the local high around Isla Mocha are enhanced by the airborne results. Although some localized artifacts may disturb the resulting image, the merged map with the SPOC and CHICAGO data now shows a detailed picture of the gravity offshore southern Chile.

11 Discussion and outlook

It was the first time that the SAF made one of their aircraft available for civilian research purposes. The collaboration with SAF and IGM in Chile was excellent and we hope to be able to continue the work with both institutions. After the re-structuring the GFZ airborne gravimetry system, this was also the first time it was used in an aircraft and tested in a survey. The new system designed proved to be very reliable both in software and hardware. Some minor design changes to the ANGEL-system are currently implemented in order to make the operation even safer and easier for the operators. The core part of the airborne gravity system works reliable and for the future only some more Novatel GPS receivers are required in order to operate all three airborne and all four ground based GPS systems with our own receivers (for this survey two receivers were borrowed and one ground station was not equipped). The marginal devices of the ANGEL system as the laser altimeter etc. should be upgraded and extended. The present laser altimeter operates nicely at low flight levels up to 300 m. In order to map topography a more powerful altimeter system is needed. Moreover, a compact, aircraft independent 3D-fluxgate magnetometer system is desirable to map the geomagnetic field parallel to the gravity field. Some basic ground based meteorological sensors to observe static and dynamic air pressure; air temperature and humidity would be of value in order to evaluate the meteorological conditions and to correct the GPS measurements for atmospheric effects. An independent ground power unit for the ANGEL system has already been acquired. This power supply will help to maintain the system on ground during the survey and enables us to simulate aircraft conditions in the laboratory in order to test the equipment. For instance, it is planned to change the power system and distribution in a way that all science instruments are hooked on an unbreakable power supply unit.

The software for data transformation and first quality checks was updated for the survey and is currently adapted to fit future requirements. For GPS processing, Trimble Total Control (TTC) proved to be reliable except in very few cases in which KSG-Soft produced results were had internal problems. An updated, re-designed version of KSG-Soft would be very helpful in the field and at the office. The aerogravity processing was revised for better handling and several options were included. Program and manual should be available on CD within this year.

The resulting data was better than expected over the onshore area. This is due to the fact that the meteorological conditions were very good and the grown experience of the pilots how to perform stable survey flights. The offshore data was expected to better a little better than now resolved. The lack of quality is to extend due to the very long GPS baselines offshore and due to some manual impacts on the gravity meter as already discussed in the former chapters. Moreover, these flights were conducted in the first part of the survey in which the pilots were still in a training phase.

With the overhauled LaCoste & Romberg gravity meter system and an autopilot equipped aircraft we therefore expect significantly better signal quality.

The scientific aims to map the ocean-continent boundary were fulfilled. The airborne gravity data shows a good correlation to those parts where reliable ground truth data is available. In combination with the ground truth data and the SPOC gravity data, a detailed new gravity map can be compiled. The second aim to map asperity structures could only be fulfilled for large-scale asperities, asperities with wavelength less than 12 km could not be resolved yet because of the line spacing (12 km) and small-scale artifacts in the data. The later problem might be solved by the integration of the strap-down gravity data, which is expected of a resolution in the range of 2 to 4 km. The processing on the strap-down data has just started. We the new system combined with an autopilot also small-scale asperity structures should be resolved. We hope to be able to continue our work in 2004 and to map the southern part of the CHICAGO survey area as displayed in Figure 11.1.

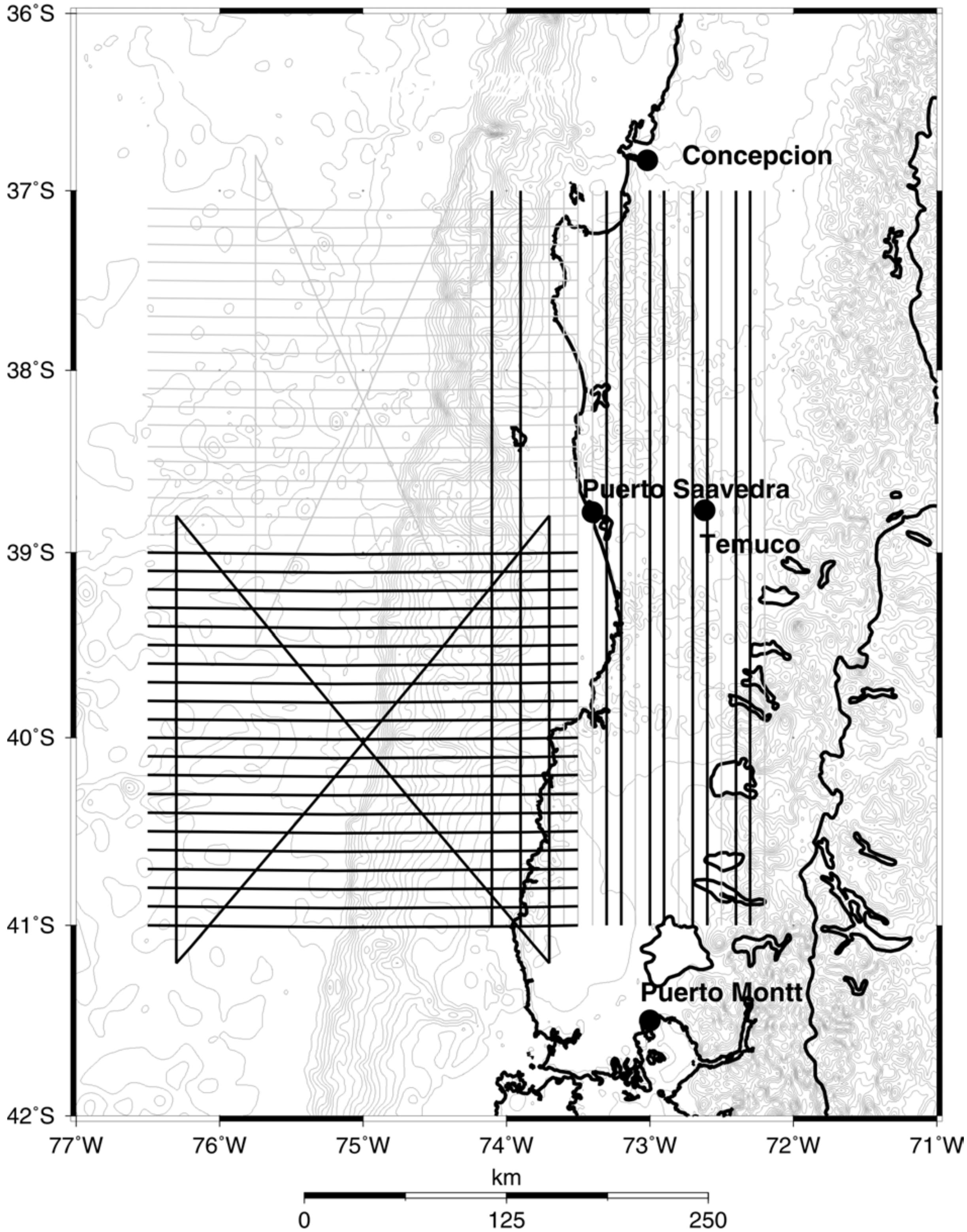

Figure 11.1: CHICAGO survey lines as planned to survey in 2004 (black lines). Topographic structures are mapped with 200 m contour lines. The survey profiles from 2002 are given in gray lines.

12 Acknowledgements

The integration of the project into the collaborative research center SFB267 as well as the financial contribution from the SFB267 made it possible to perform the onshore flights. Prof. Götze of the FU Berlin took much interest in the project and allowed his PhD-student Andres Tassara to participate. Andres Tassara was of great help as a translator, logistic manager and of course as geo-scientist in the field.

The Instituto Geográfico Militar (IGM) in Santiago was of great help in the initial organization of the survey. Moreover, the IGM's help to import and export our equipment and with the handling of the customs procedures was essential. We are very grateful for all the help and interest, especially for establishing our contact to Servicio Aerofotogrametrico (SAF).

We experienced SAF as most effective and open minded institution. The work with SAF was always a pleasure even under sometimes-complicated circumstances. The success of the survey is based to a large amount on the efforts of all SAF members participating in the project.

The GPS network of CHICAGO needed a well-established GPS reference, which we found with TIGO. All TIGO members did their best to meet our needs although their preparation time was very short. The GPS equipment at TIGO was upgraded in hard- and software within a few weeks in order to fulfill our requirements. We are very grateful for the help and expense of the TIGO team and the Bundesanstalt für Kartographie und Geodäsie.

We thank the school and headmaster in Puerto Saavedra to let us use their gymnasium hall and roof to set-up a GPS reference station and to take care of the data.

Dr. Gerd Boedecker from the Bayerische Akademie der Wissenschaften (BADW) in Munich made his strap-down gravity meter available for the survey. He especially tested and modified the data acquisition and system control software to be fit for our PC104 system. We are looking forward to present the results from his system.

We thank the Geophysical Department of the University in Kiel and the Observatory in Niemegk to send us their magnetometer systems for the survey. We are sorry that we were not able to properly implement them into our system.

Prof. Denizar Blitzkow and the SFB267 supplied onshore ground truth data that was of great importance for the data evaluation during the processing period. Offshore ground truth data was taken from the altimetry derived free-air anomaly computation of the Kort- og Matrikelstyrelsen (KMS) in Copenhagen.

For terrain mapping as well as for most the data imaging, ETOPO'2 data and GMT software was used. We thank both teams to make their sources available.

Dr. Roman Galas (GFZ) wrote most of the software for the GPS data acquisition and transformations. He was an essential partner in the survey preparation. Volker Grund (GFZ) did most of the GPS processing. His work ensured a good quality of the kinematic data. Dmitriy Marchenko (GFZ) helped in data imaging and first geoid computations. Andres Tassara (FUB) was of irreplaceable help in the field and during the CHICAGO preparations. Dr. Guochang Xu (GFZ) supplied a revised version of the formerly Unix-only KSGsoft code that now also can be used on Windows PCs.

Finally, we thank Dr. Schwintzer (GFZ), Prof. Reigber (GFZ), Prof. Oncken (GFZ) and the GFZ's directorate to support the project.

13 Annex 1

A1: Land gravity measurements (by Andres Tassara, FU Berlin)

As part of the activities carried out by the author during the first field campaign of the CHICAGO project in southern Chile, land gravity measurements have been made. This report describes the main goals, methods and results of these measurements.

A1.1 Introduction and goals

The SFB project 267 "Deformation Processes in the Andes" (SFB267) has been carried out during the last decade geo-scientific investigations in the Central and Southern active west margin of South America. The gravity group of the Institute of Geosciences of the Free University of Berlin takes part in this project throughout the acquisition, compilation, processing and interpretation of gravity data in both areas.

In the Southern Area of the SFB267 project, old gravity data from different sources have been compiled and new gravimetric stations have been measured to construct a database containing more than 15.000 gravity points. During the analysis of this information it was realized that data points presenting the same geographic positions but coming from different sources (most of them old data belonging to Chilean institutions and companies), showed notable differences in measured absolute gravity as well as in calculated Free Air and Bouguer Anomalies (until some ten mGal for the last one). These differences probably arise from unknown and dissimilar procedures in the measurement process.

The main goal of the land gravity measurements described here was to re-measure some selected and highly conflicting profiles, along roads located until some hundreds kilometers around the Aircraft Base of Temuco. These measurements were later used as control points to check the old data and decide about its incorporation in the final database.

A1.2 Methods

The land gravity measurements were made with a LaCoste & Romberg gravity meter, model G, number 998. The fabricant indicates a data resolution of 0.005 mGal, accuracy of 0.04 mGal or better, repeatability of 0.01 – 0.02 mGal and a drift of 1 mGal per month or less. The absolute position of each data point was determined with a Magellan GPS (Global Positioning System) receiver. A continuous mode measurement was used, taking 100 to 300 partial measurements for each point, which were later averaged to one value.

Six of the total days that the author was in Chile for the CHICAGO campaign, were used to made measurements along selected roads of the region near Temuco (Figure 13.1, Table 13.1). For each day (profile), the first measurement was taken in one of the two absolute gravity points depicted in Figure 13.1 with a white circle. Five of the six profiles were linked to the Temuco gravity point, which is located in the commercial airport of the city, and one profile (the northernmost one) was linked to the Victoria gravity point, located in the main square of this city.

For each profile, gravity stations were measured every 5 km along the road, except for the southernmost profile where data spacing was 10 km. In figure 1, each measurement point is showed with a small red point. In order to optimize the processing of the data, repeated measurements were made every 15 to 20 km (3 to 4 measured point).

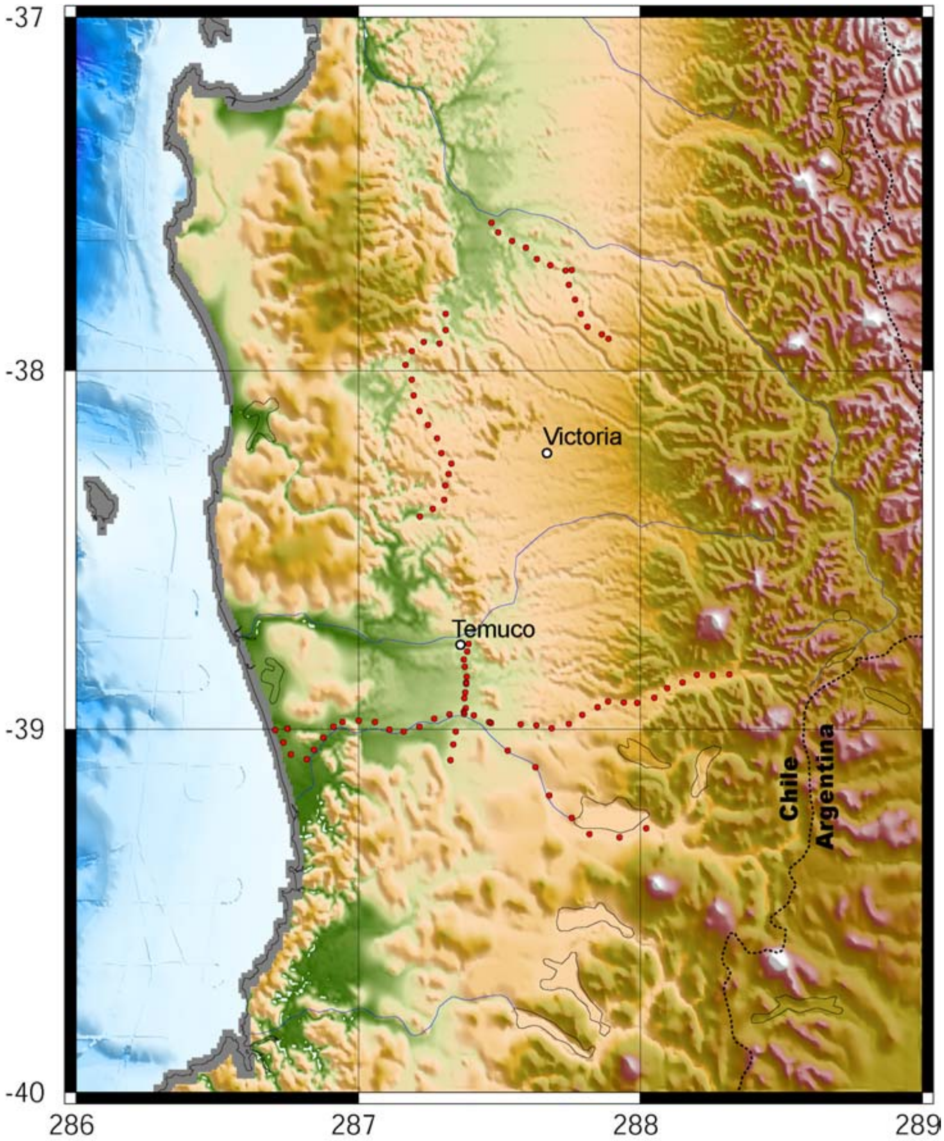

Figure 13.1: Location of measured gravity data points (black circles) and absolute gravity stations (white circles) on a shaded-relief map of the working area. Contour lines are drawn in 200 m intervals.

Table 13.1 shows the original data acquired along each profile. A total of 116 points were measured. TEM denote the absolute gravity point of the Temuco airport and VIC the one located in the city of Victoria. The measured gravity is in internal units of the G-meter.

		GPS			Gravity	
Day	Data Point	North	East	Elevation [m]	Time [hh.mm]	Measured
03.11.2002	TEM	-72,64	-38,77	88,47	11.13	3614,78
	1	-72,78	-38,41	49,68	14.41	3580,04
	2	-72,74	-38,39	235,36	15.02	3539,31
	3	-72,70	-38,37	237,53	15.17	3531,10
	4	-72,69	-38,32	126,71	15.30	3550,29
	5	-72,68	-38,29	252,01	15.45	3524,90
	6	-72,67	-38,26	189,88	15.58	3534,10
	7	-72,71	-38,23	226,44	16.08	3530,76
	8	-72,72	-38,19	282,82	16.23	3515,69

	9	-72,75	-38,15	242,45	16.33	3519,92
	10	-72,78	-38,12	174,33	16.41	3531,45
	11	-72,80	-38,07	178,09	16.50	3527,26
	12	-72,81	-38,03	148,11	17.02	3532,35
	13	-72,83	-37,99	125,63	17.12	3532,42
	14	-72,81	-37,95	121,83	17.24	3535,45
	15	-72,77	-37,92	123,30	17.34	3532,76
	16	-72,71	-37,93	138,82	17.45	3526,62
	17	-72,69	-37,89	100,40	17.55	3525,08
	18	-72,69	-37,84	120,94	18.06	3516,49
	16	-72,71	-37,93	138,98	19.15	3526,71
	13	-72,83	-37,99	126,33	19.45	3532,50
	9	-72,75	-38,15	233,35	20.03	3520,15
	5	-72,68	-38,29	251,70	20.20	3525,47
	1	-72,78	-38,41	55,90	20.50	3580,35
04.11.2002	TEM	-72,64	-38,77	89,75	11.46	3614,81
	1	-72,61	-38,77	106,38	11.58	3605,71
	2	-72,63	-38,81	93,90	12.09	3619,91
	3	-72,62	-38,86	73,51	12.17	3627,05
	4	-72,62	-38,90	91,72	12.38	3630,11
	5	-72,62	-38,94	103,62	12.50	3625,94
	6	-72,59	-38,96	110,01	13.02	3628,22
	7	-72,54	-38,98	130,32	13.10	3629,73
	8	-72,48	-39,00	143,18	13.20	3671,87
	9	-72,43	-38,99	151,34	13.30	3594,23
	10	-72,37	-38,99	179,04	13.43	3576,66
	11	-72,31	-39,00	217,67	13.55	3574,56
	12	-72,25	-38,99	250,54	14.08	3562,22
	13	-72,21	-38,96	264,88	14.27	3547,57
	14	-72,15	-38,94	299,68	14.40	3538,66
	15	-72,12	-38,93	315,43	14.57	3530,87
	16	-72,06	-38,93	355,04	15.10	3528,25
	17	-72,01	-38,93	383,71	16.20	3523,09
	18	-71,95	-38,92	419,08	16.32	3524,13
	19	-71,91	-38,89	393,92	16.43	3526,92
	20	-71,85	-38,87	407,79	16.50	3520,71
	21	-71,80	-38,85	426,65	17.00	3511,12
	22	-71,74	-38,85	455,04	17.11	3501,11
	23	-71,68	-38,85	501,94	17.30	3486,87
	22	-71,74	-38,85	440,28	18.00	3501,20
	17	-72,01	-38,93	373,28	18.30	3523,28
13.11.2002	TEM	-72,64	-38,77	107,09	12.12	3615,19
	T3-1	-72,61	-38,77	128,13	12.45	3606,62
	T3-2	-72,62	-38,79	111,63	12.58	3615,27
	T3-3	-72,62	-38,83	105,71	13.11	3627,63
	T3-4	-72,62	-38,87	112,00	13.23	3628,50
	T3-5	-72,62	-38,92	116,88	13.36	3629,72
	T3-6	-72,62	-38,96	122,47	13.48	3624,33
	T3-7	-72,66	-39,01	112,74	14.01	3628,93
	T3-8	-72,66	-39,05	115,66	14.15	3651,09

	T3-9	-72,67	-39,09	112,25	14.28	3649,61
	T3-8	-72,66	-39,05	117,42	16.06	3651,73
	T3-4	-72,62	-38,88	113,67	16.33	3629,99
	T3-1	-72,61	-38,77	134,07	16.58	3606,04
14.11.2002	TEM	-72,64	-38,77	106,70	12.57	3615,19
	T4-1	-72,63	-38,95	122,84	13.37	3623,09
	T4-2	-72,68	-38,96	108,51	13.50	3617,23
	T4-3	-72,73	-38,97	96,35	13.59	3621,61
	T4-4	-72,78	-39,00	94,18	14.10	3628,73
	T4-5	-72,84	-39,01	79,66	14.19	3630,16
	T4-6	-72,89	-39,00	68,34	14.35	3632,49
	T4-7	-72,94	-38,98	76,84	14.47	3638,64
	T4-8	-73,00	-38,98	60,55	14.56	3659,04
	T4-9	-73,06	-38,98	55,85	15.08	3660,52
	T4-10	-73,09	-39,00	42,74	16.16	3662,24
	T4-11	-73,12	-39,03	39,46	16.27	3661,87
	T4-12	-73,16	-39,06	36,17	16.38	3664,23
	T4-13	-73,18	-39,09	29,57	16.51	3666,49
	T4-14	-73,24	-39,07	31,93	17.04	3654,95
	T4-15	-73,27	-39,04	24,85	17.16	3649,64
	T4-16	-73,25	-39,00	30,58	17.29	3649,29
	T4-17	-73,29	-39,01	22,66	17.43	3637,61
	T4-15	-73,27	-39,04	29,43	18.57	3649,58
	T4-10	-73,09	-39,00	50,15	19.28	3662,21
	T4-5	-72,84	-39,01	74,91	19.49	3630,21
	T4-1	-72,63	-38,95	123,15	20.11	3623,98
15.11.2002	TEM	-72,64	-38,77	115,73	15.11	3615,20
	T5-2	-72,53	-38,99	147,52	15.48	3628,57
	T5-6	-72,24	-39,25	312,04	15.59	3630,13
	T5-9	-71,98	-39,28	243,85	16.14	3630,02
	T5-8	-72,08	-39,30	238,71	16.26	3609,91
	T5-7	-72,18	-39,29	279,12	16.41	3603,46
	T5-6	-72,24	-39,25	303,68	16.55	3589,39
	T5-5	-72,32	-39,19	243,21	17.46	3585,67
	T5-4	-72,37	-39,11	202,83	18.03	3585,62
	T5-3	-72,47	-39,06	172,38	18.26	3573,81
	T5-2	-72,53	-38,99	147,09	19.48	3589,46
	T5-1	-72,59	-38,96	131,86	20.17	3630,14
19.11.2002	VIC	-72,33	-38,23	368,06	11.44	3493,46
	T6-8	-72,27	-37,72	147,30	12.59	3489,98
	T6-12	-72,46	-37,64	105,54	14.25	3479,25
	T6-14	-72,53	-37,59	84,04	14.45	3477,92
	T6-13	-72,51	-37,61	120,34	15.04	3475,44
	T6-12	-72,46	-37,64	104,63	15.23	3460,51
	T6-11	-72,41	-37,66	102,93	15.37	3451,29
	T6-10	-72,37	-37,69	119,04	16.03	3443,36
	T6-9	-72,32	-37,71	170,01	16.33	3478,09
	T6-8	-72,27	-37,72	138,94	17.10	3489,05
	T6-1	-72,24	-37,72	133,56	17.32	3489,48
	T6-3	-72,23	-37,80	248,79	17.46	3485,06

	T6-7	-72,11	-37,91	395,52	18.01	3498,23
	T6-6	-72,14	-37,90	385,86	18.13	3497,49
	T6-5	-72,19	-37,88	347,84	18.26	3497,31
	T6-4	-72,21	-37,84	310,14	18.41	3501,83
	T6-3	-72,23	-37,80	246,04	18.59	3515,61
	T6-2	-72,25	-37,76	221,95	19.26	3497,32
	T6-1	-72,24	-37,72	147,44	20.00	3489,37

Table 13.1: Original data acquired during land gravity measurements

A1.3 Results

The original data of each profile were later processed with the program Db-Grav, developed in the Gravity group of the Free University of Berlin. This processing applies the standard gravity corrections to the measured values in order to obtain final values of absolute gravity, Free Air and Bouguer gravity anomalies for each point.

The absolute gravity points of Temuco and Victoria are tied to the IGSN71 gravity datum.

For the calculations of normal gravity the 1967 formula was used. Bouguer correction was applied with a plate density of 2670 kg/m^3 onshore and 1670 kg/m^3 offshore and a radius of 167 km. Topographic reduction and correction (Bouguer Anomaly only) were applied using a 1x1 km grid of the GTOPO'30 digital elevation model and the same densities used for the Bouguer correction.

For each profile, available repeated measurements have been compared and it has been selected the value, which minimizes the total measurement error of the whole profile (normally of the order of 0.1 – 0.01 mGal).

Table 13.2 presents the final results of each profile. These results were later used by Zuzana Tasarova of the gravity group (FU-Berlin), to evaluate the old data of the gravity database and finally to eliminate ~500 points that showed remarkable differences with the new measurements.

Day	Data Point	North	East	Elevation [m]	Gabs	Free Air [mGal]	Bouguer [mGal]
03.11.2002	TEM	-72,63908	-38,7686	101,547	980030,65	2,243	-8,339
	1	-72,78184	-38,41085	52,792	979994,738	-17,173	-21,718
	2	-72,73761	-38,39002	235,355	979952,636	-1,101	-26,586
	3	-72,69581	-38,36518	237,526	979944,15	-6,731	-32,606
	4	-72,69291	-38,32424	126,705	979963,98	-17,499	-29,158
	5	-72,68023	-38,29263	251,845	979937,738	-2,341	-18,25
	6	-72,67051	-38,26356	189,88	979947,243	-9,403	-26,128
	7	-72,70557	-38,23342	226,436	979943,788	1,074	-23,912
	8	-72,72176	-38,19278	282,816	979928,208	6,465	-20,251
	9	-72,75431	-38,15446	237,899	979932,587	0,349	-26,49
	10	-72,7846	-38,11669	174,332	979944,486	-4,052	-23,783
	11	-72,804	-38,07255	178,085	979940,151	-3,353	-21,584
	12	-72,8118	-38,02813	148,112	979945,404	-3,451	-20,148
	13	-72,83377	-37,98595	125,632	979945,428	-6,664	-19,394
	14	-72,81073	-37,94738	121,827	979948,592	-1,291	-14,581
	15	-72,76815	-37,92216	123,302	979945,804	-1,413	-11,444

	16	-72,71359	-37,92536	138,822	979939,446	-3,262	-17,564
	17	-72,69155	-37,8883	100,396	979937,848	-13,47	-24,607
	18	-72,69034	-37,84264	120,943	979928,96	-12,016	-23,785
	1	-72,60935	-38,7659	118,741	980021,231	-1,631	-13,149
	2	-72,62608	-38,81031	93,903	980035,897	1,448	-8,145
	3	-72,61679	-38,85706	73,508	980043,269	-1,604	-9,767
	4	-72,62197	-38,90181	91,715	980046,413	3,204	-6,245
	5	-72,61912	-38,94428	103,615	980042,093	-1,198	-12,019
	6	-72,59033	-38,96488	120,939	980044,441	4,675	-6,72
	7	-72,5374	-38,98351	130,319	980045,996	7,477	-4,054
	9	-72,42562	-38,98959	151,341	980009,286	-23,283	-38,044
	10	-72,36949	-38,99211	179,042	979991,12	-33,124	-50,328
	11	-72,31435	-39,00104	217,674	979988,943	-24,169	-45,149
04.11.2002	12	-72,25491	-38,98905	250,537	979976,183	-25,727	-51,15
	13	-72,20659	-38,9634	264,876	979961,033	-34,183	-62,164
	14	-72,15319	-38,9424	299,68	979951,817	-30,802	-62,064
	15	-72,1154	-38,92675	315,431	979943,757	-32,617	-67,108
	16	-72,05991	-38,92862	355,041	979941,041	-23,275	-61,646
	17	-72,01183	-38,92996	378,496	979935,648	-21,548	-63,037
	18	-71,95059	-38,91583	419,078	979936,713	-6,711	-53,077
	19	-71,90593	-38,88979	393,922	979939,583	-9,302	-51,739
	20	-71,85113	-38,87394	407,794	979933,157	-10,046	-52,867
	21	-71,80012	-38,85286	426,652	979923,233	-12,288	-58,368
	22	-71,74429	-38,8539	447,661	979912,88	-16,25	-64,988
	23	-71,68476	-38,85111	501,942	979898,13	-14,002	-66,853
	T3-1	-72,60928	-38,76591	118,741	980021,687	-1,176	-12,699
	T3-2	-72,61516	-38,78684	111,631	980030,816	3,911	-5,612
	T3-3	-72,62387	-38,83037	105,705	980043,614	11,035	1,843
	T3-4	-72,6178	-38,8732	112,836	980044,534	10,372	0,866
	T3-5	-72,62441	-38,91746	116,878	980045,816	8,989	-1,439
13.11.2002	T3-6	-72,62462	-38,96126	122,467	980040,263	1,289	-9,551
	T3-7	-72,65503	-39,01026	112,737	980045,036	-1,275	-13,476
	T3-8	-72,66342	-39,04551	116,541	980068,335	20,08	8,671
	T3-9	-72,67331	-39,08938	112,249	980066,444	12,982	3,511
	T3-8	-72,66339	-39,04549	116,541	980068,335	20,081	8,672
	T3-4	-72,61778	-38,87759	112,836	980044,534	9,984	0,398
	T3-1	-72,60926	-38,76589	118,741	980021,687	-1,174	-12,697
14.11.2002	T4-1	-72,62592	-38,95445	122,994	980038,926	0,716	-10,121
	T4-2	-72,67671	-38,96208	108,51	980032,631	-10,723	-19,787
	T4-3	-72,7322	-38,9744	96,351	980037,136	-11,06	-19,253
	T4-4	-72,78449	-38,99691	94,179	980044,469	-6,388	-12,044
	T4-5	-72,83954	-39,00909	77,286	980045,751	-11,396	-17,138
	T4-6	-72,89148	-39,00446	68,341	980048,296	-11,202	-17,028
	T4-7	-72,94163	-38,98303	76,841	980054,626	-0,354	-7,878
	T4-8	-72,99904	-38,9786	60,549	980075,691	16,075	10,659
	T4-9	-73,05725	-38,98296	55,85	980077,195	15,744	15,179
	T4-10	-73,08887	-38,99679	46,443	980078,755	13,177	8,151
	T4-11	-73,1249	-39,02652	39,463	980078,447	8,085	5,326
	T4-12	-73,15882	-39,0601	36,171	980080,871	6,522	4,555
	T4-13	-73,18414	-39,08619	29,567	980083,191	4,495	2,159

	T4-14	-73,23931	-39,07338	31,933	980071,248	-5,584	-8,678
	T4-15	-73,26747	-39,03984	27,14	980065,685	-9,658	-11,981
	T4-16	-73,25111	-39,00188	30,584	980065,374	-5,548	-7,362
	T4-17	-73,29483	-39,00533	22,657	980053,291	-20,382	-22,13
	T4-15	-73,26755	-39,03971	27,14	980065,685	-9,646	-11,966
15.11.2002	T5-9	-71,97961	-39,27767	243,853	979987,875	-41,652	-65,208
	T5-8	-72,07522	-39,30214	238,708	980000,085	-33,199	-56,709
	T5-7	-72,18057	-39,2928	279,118	980000,141	-19,844	-48,814
	T5-6	-72,24417	-39,2481	307,86	980004,009	-3,145	-35,058
	T5-5	-72,32306	-39,18597	243,208	980018,537	-3,064	-24,883
	T5-4	-72,37347	-39,10817	202,831	980025,203	-1,969	-23,075
	T5-3	-72,47098	-39,0628	172,377	980045,987	13,433	-3,36
	T5-2	-72,53069	-38,98596	147,304	980046,085	12,591	-0,768
	T5-1	-72,5903	-38,96489	120,939	980044,482	4,715	-6,68
19.11.2002	VIC	-72,33206	-38,23402	368,062	979904,86	5,8	-34,688
	T6-14	-72,52897	-37,58571	84,036	979927,93	-1,954	-9,737
	T6-13	-72,50522	-37,61241	120,337	979913,697	-7,318	-20,052
	T6-12	-72,45508	-37,63641	105,086	979909,023	-18,797	-27,072
	T6-11	-72,40676	-37,65546	102,933	979909,22	-20,93	-30,256
	T6-10	-72,3669	-37,68774	119,038	979909,987	-18,016	-30,389
	T6-9	-72,31957	-37,70586	170,005	979896,38	-17,48	-36,219
	T6-8	-72,26598	-37,72024	143,124	979900,863	-22,551	-37,19
	T6-7	-72,11358	-37,91212	395,521	979853,268	-9,06	-52,8
	T6-6	-72,13697	-37,90005	385,857	979861,448	-2,804	-44,983
	T6-5	-72,18837	-37,87933	347,842	979870,966	-3,202	-41,526
	T6-4	-72,21185	-37,84291	310,139	979886,38	3,768	-27,481
	T6-3	-72,23183	-37,80257	247,417	979889,048	-9,387	-33,419
	T6-2	-72,25384	-37,76051	221,954	979890,288	-12,323	-34,465
	T6-1	-72,24444	-37,71976	140,503	979901,308	-22,873	-35,44

Table 13.2: Processed gravity data along each profile (computed by Zuzana Tasarova, FUB)

14 Annex 2

A2: Geoid computations (by Dmitriy Marchenko, GFZ)

During the course of the CHICAGO survey, some work was carried out at the Instituto Geográfico Militar in Santiago in order compute a regional geoid model for the metropolitan part of Chile, around Santiago and for the area of investigation. This co-operation went along with the airborne work.

The existing land gravity database was carefully analyzed and updated with new data given by IGM. Data points with artifacts were deleted from the initial file. Original sparse marine offshore data were replaced by using KMS'99 2'×2' gravity anomalies inverted from satellite altimetry. As a result, the new 3.5′×3.5′ mean gravity anomalies were computed for the area from 30°S to 36°S by latitude and from 78°W to 60°W by longitude. Residual gravity field was derived by applying of the terrain correction to the newly computed mean free–air gravity anomalies and reducing of the EGM'96 (n=360) global gravity model. The ETOPO'2 digital terrain model was used for the computation of the terrain correction (Figure 14.1).

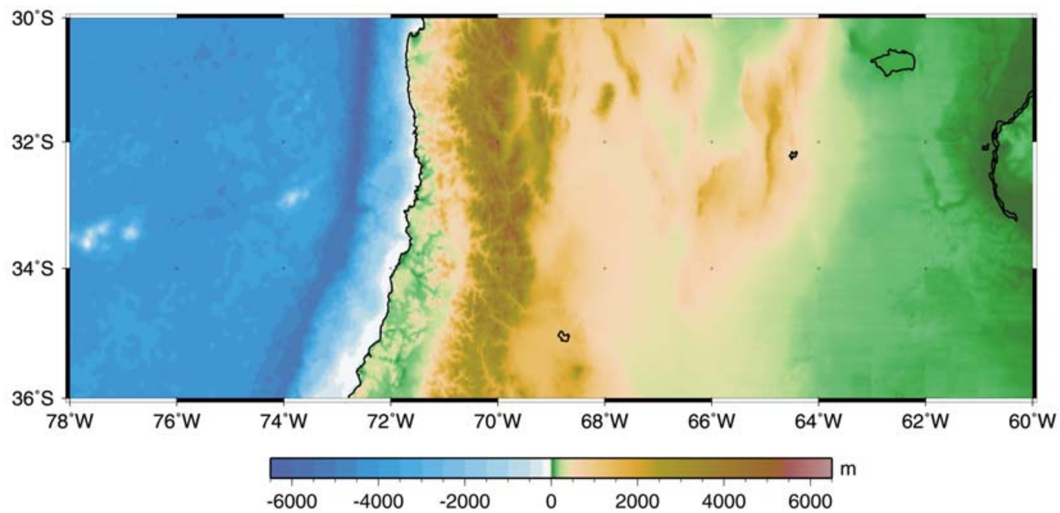

Figure 14.1: ETOPO'2 digital elevation model for the "metropolitan" area Chile. Contours are given each 200 m.

The sequential multipole analysis approach (SMA) [Marchenko et al, 2000] for the geoid determination was applied in the following way. A direct approximation of residual gravity anomalies by means of radial multipole potentials of different degrees was derived for the construction of a corresponding preliminary model (gravimetric geoid only). The multipole model consisted of 3576 multipole moments with an accuracy of about 2.5 mGal. In the next step this model was used for the re-adjustment of the multipole moments for the following heterogeneous sets of data: Faye gravity anomalies over the land and KMS – SSH (interpolated at the same grid mean Sea Surface Heights) over the ocean (gravimetry/altimetry solution). The newly re-adjusted geoid (Figure 14.2) model was compared with the EGM'96 global model. The resulting statistics are given in Table 1.

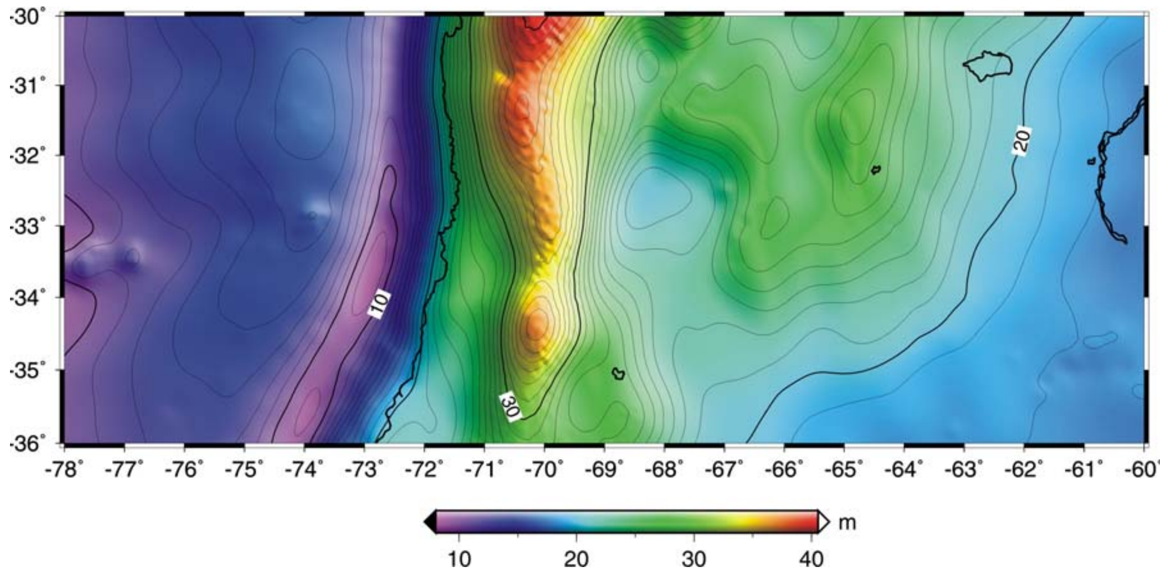

Figure 14.2: Gravimetric/altimetry geoid solution for the "metropolitan" area around Santiago. Contour lines are drawn at every 1 m.

	Min	Max	Mean	Std. Dev
SMA-EGM	-0.9	1.60	0.05	0.25

Table 14.1: Comparison of SMA model with EGM'96 global model for the "metropolitan" area

The geoid model for the southern Andes was also constructed using the sequential multipole analysis in two steps. In the first step newly computed 6′×6′ free-air gravity anomalies were terrain corrected using the ETOPO'2 digital elevation model. For further smoothing of the data in the frame of remove-restore technique, the EGM'96 (360,360) global gravity model was used. The preliminary geoid model consisted of 8350 multipole moments and positions with an estimated accuracy of 0.5-1.0 mGal. In the second step the derived geoid model was re-adjusted with original land based gravity anomalies and KMS'99 sea surface heights. The resulting geoid model (Figure 14.3) was compared with GPS/leveling data and EGM'96 global gravity model. The statistics of this comparison are given in Table 14.2.

	$N_{SMA} - N_{EGM'96}$	$N_{SMA} - N_{GPS}$	$N_{EGM'96} - N_{GPS}$
Min	-2.70	-0.45	-0.70
Max	1.27	0.02	0.25
Average (m)	-0.02	-0.15	0.18
σ (m)	0.47	0.20	0.39

Table 14.2: Comparison of SMA model with EGM'96 global model and GPS/leveling data.

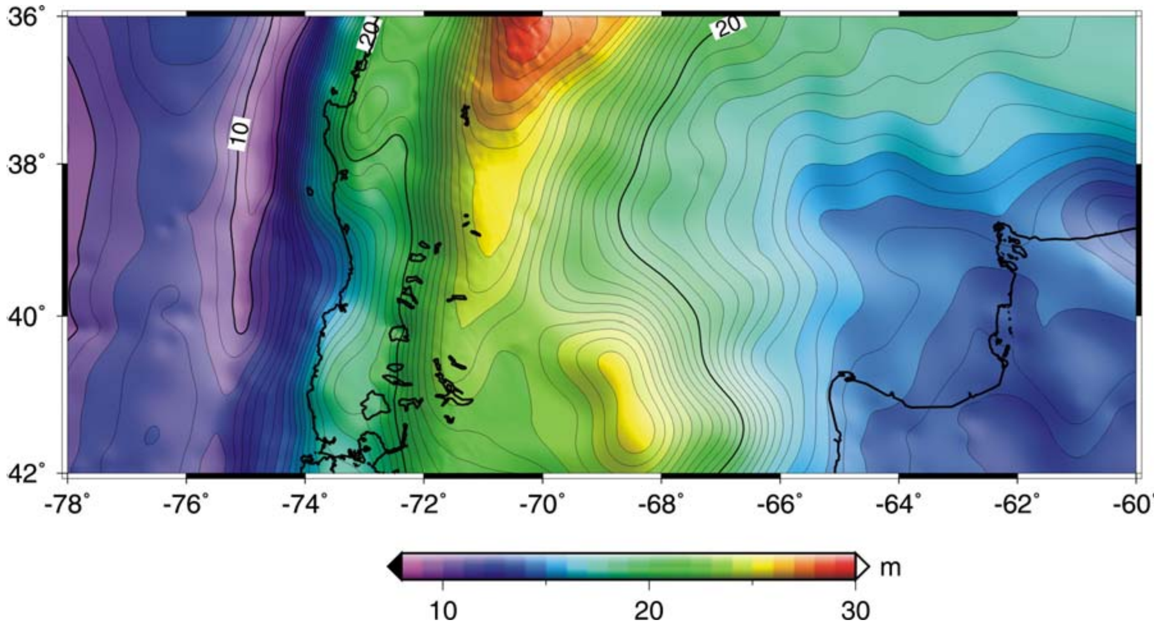

Figure 14.3: Gravimetric/altimetry geoid solution for the Southern Andes. Contour lines are drawn at every 1m.

15 Annex 3

A3: Co-operation agreement (German/English/Spanish)

A3.1 Wissenschaftliche Einbindungen und Zielsetzungen

Das Projekt CHICAGO wird von deutscher Seite aus betrieben vom GFZ Potsdam, Projektbereich 1.3 "Figur und Schwerefeld der Erde". Das Vorhaben wird unterstützt durch personelle wie finanzielle Hilfe des SFB-267, hierin insbesondere der FU Berlin. Die chilenischen Projektpartner sind das Instituto Geografico Militar und die Fuerza Aerea de Chile, Servicio Aerofotogrametrico.

Das Vorhaben CHICAGO ist eng an bestehende und geplante wissenschaftliche Langzeituntersuchungen geknüpft, die am GFZ Potsdam und Partnereinrichtungen betrieben werden. Dazu zählt insbesondere der Sonderforschungsbereich SFB-267 "Deformationsprozesse in den Anden" sowie das geplante TIPTEQ-Projekt "from The Incoming Plate to mega-Thrust Earthquake processes". Der SFB-267 besteht seit etwa 10 Jahren und hat umfangreiche geologische, geophysikalische und geodätische Daten im Bereich der Zentral- und Südanden gesammelt. In der jetzigen Schlussphase des SFB-267 wird verstärkt auf die Interpretation und die Modellierung der Daten hingearbeitet. Daran sind auch Mitarbeiter des Projektbereichs 1.3 beteiligt, die sich insbesondere der Geoid-Modellierung der Anden und des südamerikanischen Kontinents widmen. Das TIPTEQ-Vorhaben von Geomar und GFZ zielt auf die Bestimmung von Prozessen, die innerhalb der Subduktionszone der südamerikanischen Westküste Erdbeben auslösen. Auch hier werden die CHICAGO-Messungen eine große Rolle spielen.

Das Untersuchungsgebiet für die CHICAGO-Befliegung in 2002 konzentriert sich auf das Gebiet zwischen 37° S und 39° S. Eine der Kernaufgaben des Projektes ist die Kartierung der sich verändernden Subduktion, Ozeanrinne und Küstenstruktur um etwa 40° S. Entlang der Zentralanden bestimmen eine tiefe Ozeanrinne, ein schmaler Schelf und hohe Plateaus das Bild. Südlich von 40° S verflacht die Ozeanrinne, der Schelf wird breiter und die Gebirgszüge weniger prominent. Zusätzlich werden in der Küstenregion um 40° S nur schwache gravimetrische Anomalien beobachtet. Nördlich und südlich davon ziehen sich stark positive Bouguer-Anomalien an der Küste entlang. In 2002 soll die nördliche Teil der sich verändernden Strukturen mit aero-geophysikalischen Methoden erfasst werden, wenn möglich in 2003 der südliche Teil.

Ein weiterer Kernpunkt ist der Versuch, über Aerogravimetrie "asperities" (Rauhigkeiten) besonders in der ozeanischen Platte des Pazifik zu kartieren. "Asperities" sind Teilstücke der Platte, die mehr Spannungen aufnehmen und speichern können als ihre Umgebung. Es besteht die Vermutung, dass solche Teilstücke während der Subduktion plötzlich ihre Spannung entladen und damit Erdbeben triggern. Ihre typische räumliche Ausdehnung wird auf einige 10 Kilometer im Quadrat geschätzt. In neueren Diskussionen wird vermutet, dass solche "asperities" mit positiven Bouguer-Anomalien verknüpft sind. Mit Hilfe der Aerogravimetrie soll nun versucht werden, solche Strukturen zu kartieren.

Parallel zu der aerogravimetrischen Komponente der Befliegung soll während der Flüge über Wasser auch mit einem Laser-Höhenmesser die Meeresoberfläche vermessen werden. Dieser Datensatz dient der Berechnung bathymetrischer Strukturen und dem Vergleich zu Satellitendaten.

A3.2 Datenaustausch, Verantwortlichkeiten und Kosten

2.1 Datenaustausch

Das aerogeophysikalische Projekt CHICAGO zielt darauf hin das Schwerefeld – und wenn technisch machbar – das Magnetfeld über der Küstenregion von Chile zu befliegen. Die Daten werden genutzt, um die Dynamik des Ozean-Kontinent-Überganges an einem konvergenten Plattenrand zu studieren, Schwere- und Magnetfeld zu kartieren, Beiträge zu Erdbebenmechanismus-Studien zu liefern, sowie zu geodätischen Kartierungen und Geoid-Modellierungen. Die Daten sind offen für den Austausch zwischen den beteiligten Institutionen GFZ, IGM und SAF und deren Projekte. GFZ, IGM und SAF müssen gemeinsam zustimmen, wenn die Daten der Kampagne an Institutionen weitergegeben werden, die nicht am Projekt CHICAGO beteiligt sind. Alle weiteren Datenprodukte die direkt aus den Kampagnendaten erzeugt werden, sind für SAF, IGM und GFZ frei zugänglich.

2.2 Verantwortlichkeiten des GFZ

Das GFZ stellt alle wissenschaftlichen Geräte zur Verfügung, die zum Erreichen der Zielsetzungen der Kampagne CHICAGO notwendig sind: Rechnereinheiten, wissenschaftliche Flugzeugausrüstung und Landstationen, sofern diese nicht in Chile verfügbar sind. Das GFZ wird alle notwendigen Dokumentation der wissenschaftlichen Ausrüstung für das Flugzeug bereitstellen. Das GFZ wird alle notwendigen Programme zur Erreichung der Ziele von CHICAGO zur Verfügung stellen. Das GFZ wird aktiv die Qualitätskontrolle der Daten im Feld und die spätere Detailprozessierung übernehmen. Das GFZ ist verantwortlich für die Frachten und Zollerklärungen über eine Spedition, die durch das GFZ bestimmt wird. Alle Frachtinhalte werden dem IGM vorab zugesandt.

2.3 Verantwortlichkeiten des IGM

Das IGM ist zusammen mit dem GFZ für die Aufstellung und den Betrieb der Landstationen verantwortlich, die für die Flugkampagne CHICAGO notwendig sind. Das IGM wird hierzu Personal bereitstellen falls erforderlich. Das IGM ist für eine kampagnenbezogene Kooperationsvereinbarung mit der SAF verantwortlich, die Details der Flugzeugnutzung inklusive Crew, Treibstoffversorgung, Installationen, Daten und Geldtransfer regelt. Das IGM ist verantwortlich für die Lagerung der Frachten des GFZ und den Transport zur SAF für den Einbau ins Flugzeug. Das IGM ist verantwortlich für den Transport der notwendigen Ausrüstung vom SAF / IGM-Lager in Santiago de Chile zur Operationsbasis der Flugkampagne.

2.4 Verantwortlichkeiten der SAF

Die SAF ist verantwortlich für die Flugzeugnutzung inklusive Einbau der wissenschaftlichen Geräte und Flugbetrieb. Die SAF ist verantwortlich für die Flugsicherheit, Notfallausrüstung und SAR-Maßnahmen. Das GFZ wird Adapterplatten für alle Kabineneinbauten liefern um das wissenschaftliche Gerät zu fixieren. Die SAF ist verantwortlich dafür, die Adapterplatten im Flugzeug zu haltern. IGM und SAF sind gemeinsam dafür verantwortlich, einen Büroraum am Flugplatz der Operationsbasis zu stellen. Alle weiteren Details sind Bestandteil der Kooperationsvereinbarung zwischen SAF und IGM.

2.5 Kosten

Das GFZ übernimmt alle Kosten für die Flugkampagne CHICAGO im Jahr 2002 betreffend Frachten, Installation der Ausrüstung im Feld und im Flugzeug. Das GFZ übernimmt alle Kosten für die vier Kampagnenteilnehmer des GFZ und der FU Berlin im Feld. Das GFZ übernimmt die Flugbetriebskosten für die Kampagne CHICAGO. Weitere Kosten, die aus verschiedenen Gründen über die Zielsetzungen des Projektes CHICAGO hinausgehen, müssen durch IGM und SAF gedeckt werden. Der Geldtransfer des GFZ zur Bezahlung der entsehenden Kosten im Jahr 2002 wird über das IGM geregelt. GFZ, IGM und SAF sind gemeinsam dafür verantwortlich, dass die Kampagnenkosten im vereinbarten Rahmen bleiben.

A3.3 Logistik

3.1 Flugplanung

Die allgemeine Flugplanung wird etwa einen Monat vor Kampagnenbeginn in gemeinsamer Absprache zwischen GFZ, IGM und SAF festgeschrieben. Änderungen der Flugplanung aus Wettergründen, logistischen Gründen oder wissenschaftlichen Gründen bedürfen der Zustimmung durch IGM und SAF. Die Operationsbasis für die Flugkampagne CHICAGO in 2002 wird Temuco sein.

2.3 Kampagnenbeschreibung 2002

Dieser Abschnitt beschreibt den Rahmen der aerogeophysikalischen Kampagne CHICAGO im Jahr 2002 (siehe Abbildung 1). Das Zielgebiet über Wasser ist begrenzt durch die folgenden Koordinaten: 39°S bis 37°S und 73,5°W bis 77°W. Die Flughöhe beträgt 3000 ft über Land und 1000 ft über Wasser. Die Profile über Wasser laufen in E-W-Richtung mit einem Fluglinienabstand von 6 nM. Ein X-förmiger Flug soll diese Linien kreuzen. Das Zielgebiet über Land ist begrenzt durch die folgenden Koordinaten: 41°S bis 37°S und 73,7°W bis 72,8°W. Die Profile über Land laufen in N-S-Richtung mit einem Fluglinienabstand von 6 nM. Die Flugzeug-Einrüstung findet in Santiago statt. Operationsbasis ist Temuco. Bodenstationen für GPS sollen in Temuco, Concepcion und Puerto Montt und Lemu betrieben werden. Eine Magnetik-Bodenreferenz soll in Temuco betrieben werden. Die Flugoperation soll zwischen dem 1.11. und dem 30.11.2002 erfolgen. Es werden nur so viele der geplanten Flüge auch ausgeführt, dass die Projektkosten im beantragten Rahmen bleiben.

A3.4 Scientific Links and Aims

The project CHICAGO is planned and carried out by the GFZ Potsdam, Section 1.3 "Figure and Gravity Field of the Earth". The intention is supported in terms of finances and personnel by the SFB-267, herein especially by the FU Berlin. The Chilean project partners are the Instituto Geografico Militar and the Fuerza Aerea de Chile, Servicio Aerofotogrametrico.

The project CHICAGO is closely connected to existing and planned long term scientific studies of the GFZ Potsdam and partner institutes. This especially accounts for the collaborative research project SFB-267 "Deformation Processes in the Andes" and as well for the planned project TIPTEQ "from The incoming Plate to mega-Thrust Earthquake processes". The SFB-267 already exists for about ten years and within this time has collected a vast amount of geological, geophysical and geodetic data in the central and southern Andes. In the present final phase of the SFB-267 the work is focused on interpretation and modeling efforts. Members of the Section 1.3 are involved in this work, working on geoid models for the Andes and the South American continent. The TIPTEQ project of Geomar and GFZ aims to determine processes that trigger earthquakes in the subduction zone along the western coast of South America. The CHICAGO survey will provide important data to support these studies.

The main task of the project is to map the changing subduction, trench and coastal structure around 40° S. Whereas along the central Andes a deep trench system, a narrow shelf area and high plateaus are evident, south of 40° S the trench gets narrow and shallow, the shelf widens and only minor mountain belts are to be found. Moreover, in the transition zone around 40° S we observe only weak gravity anomalies along the coast. North and south of this region strong positive anomalies follow the coastline.

Another attempt connected with this aero-survey is to try to map asperity structures of the Pacific Ocean plate. Asperities are patches of the plate that are able to accumulate more stress than its environment. Such plate structures might trigger earthquakes when the stress is released during subduction. Their typical extend is believed to be some ten kilometers in square. In recent discussions the theory developed, that these asperities are connected with positive Bouguer anomalies. The aerogravimetric survey part offshore Chile is therefore also meant to try to identify such structures.

Parallel to the aero-geophysical components of the survey it is planned to map the ocean surface along the flight pattern with high-resolution altimetry. This data in conjunction with the airborne gravity data can be used to test algorithms to compute the bathymetric structure.

A3.5 Data Policy, Responsibilities and Costs

2.1 Data Policy

The aero-geophysical project CHICAGO aims to map the gravity and - if technically possible - the magnetic field over the coastal areas of Chile. The data will be used to study the dynamics of the ocean-continent boundary at convergent margins, to map gravity and magnetic anomaly fields, to contribute to earthquake mechanism studies, for geodetic mapping and geoid computations. The data will be shared between IGM, SAF and GFZ and is free for usage in any projects IGM, SAF and GFZ are directly involved in. IGM, SAF and GFZ have to mutually agree if the data is to be given to any institution outside the co-operation partnership of the three institutions named above. All data products directly derived from this survey will be distributed freely within IGM, GFZ and SAF.

2.2 Responsibilities of GFZ

The GFZ will supply all scientific hardware necessary to cover the aims of the project CHICAGO: computer facilities, scientific aircraft instrumentation and ground based stations if not available in Chile. The GFZ will supply all necessary technical documentation on the scientific hardware used in the airborne installation. The GFZ will supply all necessary software to cover the aims of the project CHICAGO. The GFZ will actively contribute personnel to the field program and later data processing at the institutes. The GFZ will be responsible for data quality control and archiving in the field. The GFZ will be responsible for the freight transfer and customs declarations through a freight agency chosen by GFZ. All freight descriptions will be send by GFZ to IGM ahead of the freight delivery.

2.3 Responsibilities of IGM

The IGM together with GFZ will be responsible to set-up and maintain the ground-based stations necessary for the aero-geophysical project CHICAGO. The IGM will supply personnel in the field if necessary. The IGM will be responsible to set-up a co-operation agreement with SAF that handles the details of the aircraft usage including crew, fuel, installations, data and money transfer. The IGM will be responsible to store the shipped freight from GFZ and to transfer it to SAF for installation. The IGM will be responsible to transfer all necessary equipment from SAF / IGM headquarters in Santiago de Chile to the base of flight operations. The IGM in accordance with SAF will be responsible for accommodation of the CHICAGO crew in Santiago de Chile and at the base of flight operations.

2.4 Responsibilities of SAF

The SAF will be responsible for all aircraft handling including scientific hardware installations and flight operations. The SAF will be responsible for flight security, emergency equipment and SAR measures. The GFZ will supply adapter plates for all cabin installations and be responsible to fix the scientific instruments on the plates. The SAF is responsible to fix the plates with instruments in the aircraft. IGM together with SAF will be responsible to supply an office room on the base of operation. All other details concerning SAF responsibilities within the project CHICAGO will be subject of an individual statement of agreement or contract between SAF and IGM.

2.5 Costs

The GFZ will cover all costs of the aero-geophysical project CHICAGO in the year 2002 for freight shipment, installation of the equipment in the field and on the aircraft. The GFZ will cover costs for four team members of the GFZ and FU Berlin in the field. The GFZ will cover the flight operation costs. Other costs that emerge from activities of IGM and SAF that are beyond the details of the aero-geophysical survey must be covered by IGM or SAF. All money transfers from GFZ to cover the costs of the project in the year 2002 will be handled by IGM. All partners are responsible to keep the operation costs within the general budget of the survey.

A3.6 Logistics

3.1 Flight Planning

The general flight plans will be defined at least one month ahead of the start of flight operations within a mutual agreement of GFZ, IGM and SAF. Changes of the flight plan in the field due to weather, logistics or scientific reasons have to be approved by IGM and SAF. The base of operation will be mutually agreed upon by GFZ, IGM and SAF.

3.2 Survey Description

This paragraph describes the frame of the aero-geophysical project CHICAGO in the year 2002. The area of interest within CHICAGO'2002 is limited offshore by the following boundaries: 37°S to 39°S and 73.5°W to 77°W. The flight altitude is fixed on 1000 ft above sea level, weather permitting. The profile directions are E-W with a flight line spacing of 6 nautical miles. Tie lines crossing the profiles are based on an X-pattern (see map). The area of interest within CHICAGO'2002 is limited onshore by the following boundaries: 37°S to 41°S and 73.7°W to 72.8°W. The profile directions are N-S with a flight line spacing of 6 nautical miles. Base of flight operation is Temuco airbase. Base of aircraft installation and de-installation is Santiago de Chile. The transfer flights between Santiago de Chile and Temuco will be used for profile measurements. Ground based GPS stations will be supplied in Temuco, Conception, Puerto Montt and Lemu. The estimated flight operation time starts November 1st 2002 and should end November 30th 2002. Only those flights that are planned will also be flow that are covered by the requested project funding.

A3.7 Contactos Cientificos y Objetivos

El proyecto CHICAGO es planeado y llevado a cabo por el GFZ Potsdam, sección 1.3 "Figura y Campo Gravimétrico de la Tierra". Este proyecto es auspiciado en términos financieros y de personal por el SFB-267, especialmente por la FU Berlin. La contraparte chilena la constituyen el Instituto Geográfico Militar (IGM) y el Servicio Aerofotogramétrico de la Fuerza Aérea de Chile (SAF).

El proyecto CHICAGO está profundamente conectado con estudios científicos existentes de larga data y otros en planes, especialmente con el proyecto de investigación colaborativa SFB-267 "Procesos de Deformación en los Andes" y con el planeado proyecto TIPTEQ " from The Incoming Plate to mega-Thrust Earthquake processes". EL SFB-267 existe hace ya 10 años y dentro de este tiempo ha colectado una vasta cantidad de datos geológicos, geofísicos y geodéticos en los Andes Centrales y del Sur. En la fase final en curso del SFB-267 el trabajo se concentra en esfuerzos de modelación e interpretación. Miembros de la sección 1.3 están involucrados en esta tarea, trabajando en modelos del geóide para los Andes y el continente Sudamericano. TIPTEQ de Geomar e GFZ intenta determinarse los procesos que gatillan los terremotos en la zona de subducción a lo largo de la costa oeste de Sudamérica. CHICAGO proveerá importantes datos para la realización de estos proyectos.

La tarea principal del proyecto es mapear la estructura cambiante de la subducción, fosa y costa en torno a los 40°S. Mientras a lo largo de los Andes Centrales son evidentes un sistema profundo de fosa, una delgada área de plataforma y un elevado plateau continental, al sur de los 40°S la fosa se hace mas delgada y superficial, la plataforma se ensancha y sólo pequeñas cadenas montañosas son reconocibles. Más aun, en la zona de transición en torno a los 40°S observamos sólo una débil anomalía gravimétrica a lo largo de la costa. Hacia el norte y sur de esta región fuertes anomalías positivas siguen la línea de costa.

Otro objetivo conectado con esta campaña aérea es tratar de mapear estructuras de aspereza de la placa oceánica. Las asperezas son parches de la placa que son capazes de acumular más stress que su entorno. Estas estructuras de la placa pueden gatillar terremotos cuando el stress es liberado durante la subducción. Su tamaño típico se cree es del orden de algunas decenas de kilómetros cuadrados. En discusiones teóricas recientes se ha establecido que estas asperezas están conectadas con anomalías de Bouguer positivas. La parte costa a dentro del levantamiento aerogravimétrico está por tanto también pensada para tratar de identificar estas estructuras.

Paralelamente con la componente aero-geofísica del levantamiento está planeado mapear la superficie del océano a lo largo de las líneas de vuelo con altimetría de alta resolución. Estos datos en conjunto con la aerogravimetría pueden ser usados para testear algoritmos para computar la estructura batimétrica.

A3.8 Política de Datos, Responsabilidades y Costos

2.1 Política de Datos

El proyecto aéro-geofísico CHICAGO pretende mapear la gravedad y - si es técnicamente posible - el campo magnético sobre las áreas costeras de Chile. Los datos serán usados para estudiar la dinámica de la frontera océano - continente en márgenes convergentes, para mapear anomalías gravimétricas y magnéticas, para contribuir al estudio de mecanismos de sísmos, para mapeo geodético y cálculo del geóide. Los datos serán compartidos por IGM, SAF y GFZ y son de libre uso en cualquier proyecto en el que estas instituciones esten directamenmte involucradas. IGM, SAF y GFZ deben acordar mútuamente el traspaso de datos a cualquier otra institución que no pertenesca al grupo de cooperación definido por ellas tres. Todos los datos y productos directamente derivados de este levantamiento serán distribuidos libremente entre IGM, SAF y GFZ.

2.2 Responsabilidades de GFZ

GFZ proveerá todo el hardware científico necesario para cubrir los objetivos del proyecto CHICAGO: instalaciones computacionales, instrumentación científica del avión y estaciones de tierra si no están disponibles en Chile. GFZ proveerá toda la documentación técnica necesaria sobre el uso del hardware científico en la instalación del avión. GFZ proveerá todo el software necesario para cubrir los objetivos del proyecto CHICAGO. GFZ contribuirá activamente con personal para el programa de terreno y posterior procesamiento de datos en los institutos. GFZ será responsable del control de calidad de los datos y su archivación en terreno. GFZ será responsable de la transferencia de la carga y las declaraciones de aduana a travéz de una agencia especializada elegida por el GFZ. Toda la descripción de la carga será enviada por GFZ a IGM antes de la recepción de la carga.

2.3 Responsabilidades de IGM

IGM junto con GFZ serán responsables de instalar y mantener las estaciones de tierra necesarias para el proyecto aero-geofísico CHICAGO. IGM aportará personal en terreno si es necesario. IGM será responsable de activar un acuerdo de co-operación con SAF que estipule los detalles del uso del avión incluyendo la tripulación, el combustible, instalaciones, traspaso de datos y dinero. IGM será responsable de almacenar la carga enviada por GFZ y de transferirla a SAF para su instalación. IGM será responsable de transferir todos los equipos necesarios desde las oficinas de IGM/SAF en Santiago de Chile a la base de operaciones aéreas. IGM, en acuerdo con SAF, será responsable de las acomodaciones de la tripulación de CHICAGO en Santiago y en la base de operaciones aéreas.

2.4 Responsabilidades de SAF

SAF será responsable de todo lo relacionado con la operación del avión, incluyendo la instalación del harware científico y la operación de vuelo. SAF será responsable de la seguridad en vuelo, equipos de emergencia y las mediciones SAR. GFZ proveerá plataformas de adapatación para todas las instalaciones en cabina y será responsable de fijar los equipos científicos en dichas plataformas. SAF será responsable de fijar las plataformas con instrumentos en el avión. IGM junto con SAF serán responsables de proveer una oficina en la base de operaciones. Otros detalles con respecto a las resposabilidades de SAF dentro del proyecto CHICAGO serán objeto de un acurdo o contrato individual entre SAF e IGM.

2.5 Costos

GFZ cubrirá todos los costos del proyecto aero-geofísico CHICAGO en el año 2002 relacionados con embarco de carga, instalación de los equipos en el terreno y en el avión. GFZ cubrirá costos de estadía en terreno de cuatro miembros del GFZ y la FU Berlín. GFZ cubrirá los costos de operación en vuelo. Otros costos generados por actividades de IGM y SAF que esten más allá de los detalles de la campaña aero-gefísica deben ser cubiertos por IGM o SAF. Todo el dinero transferido por GFZ para cubrir los costos del proyecto en el año 2002 serán administrados por IGM. Todos los miembros del proyecto son responsables de mantener los costos de operación dentro del presupuesto general de la campaña.

A3.9 Logística

3.1 Plan de Vuelo

El plan general de vuelo será definido a más tardar un mes antes del comienzo de las operaciones de vuelo dentro de un acuerdo mútuo entre GFZ, IGM y SAF. Cambios en el plan de vuelo en terreno debidos al clima, logística o razones científicas tiene que ser aprovadas por IGM y SAF. La base de operaciones será mútuamente acordada por GFZ, IGM y SAF.

3.2 Descripción del Levantamiento

Este párrafo describe el marco del proyecto aéro-geofisico CHICAGO en el año 2002 (ver figura 1). El área de interés de CHICAGO´2002 está limitada costa a fuera por los siguientes límites: 37°S a 39°S y 73.5°W a 77°W. La altura de vuelo se fija en 3000 pies sobre la tierra y 1000 pies sobre el nivel del mar, si el clima lo permite. La dirección de los perfiles es EW con un espaciamiento de líneas de vuelo de 6 millas náuticas. Líneas de control cruzando los perfiles se basan en un trazado tipo X. El área de interés de CHICAGO´2002 está limitada costa a dentro por los siguientes límites: 37°S a 41°S y 73.7°W a 72.8°W. La dirección de los perfiles es NS con un espaciamiento de líneas de vuelo de 6 millas náuticas. La base de operaciones de vuelo es la basde aérea de Temuco. La base de instalación y desinstalación del avión es Santiago de Chile. Los vuelos de transferencia entre Santiago y Temuco serán usados para mediciones de perfiles. Estaciones GPS en tierra serán suministradas en Temuco, Concepción, Puerto Montt y Lemu. Un punto magnético de referencia en tierra debe ser instalado. El tiempo estimado de operaciones de vuelo comienza el 1ro de Noviembre del 2002 y debería terminar el 30 de Noviembre del 2002. Se volarán tantos vuelos planificados como los necesarios para mantener los costos del proyecto dentro del marco financiero requerido.

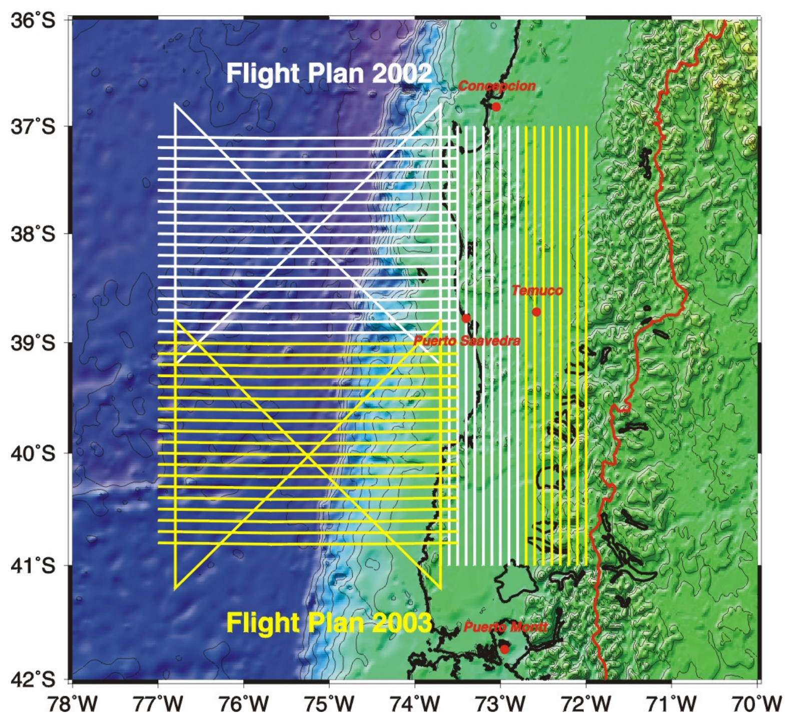

Figure 15.1: Flight Plan

Planned Flights 2002	Longitude	Latitude	
Flight 1 Profile 1	-077.0	-38.9	Offshore
	-073.5	-38.9	
Flight 1 Profile 2	-077.0	-39.0	
	-073.5	-39.0	
Flight 2 Profile 1	-077.0	-38.7	
	-073.5	-38.7	
Flight 2 Profile 2	-077.0	-38.8	
	-073.5	-38.8	
Flight 3 Profile 1	-077.0	-38.5	
	-073.5	-38.5	
Flight 3 Profile 2	-077.0	-38.6	
	-073.5	-38.6	
Flight 4 Profile 1	-077.0	-38.3	
	-073.5	-38.3	
Flight 4 Profile 2	-077.0	-38.4	
	-073.5	-38.4	
Flight 5 Profile 1	-077.0	-38.1	
	-073.5	-38.1	
Flight 5 Profile 2	-077.0	-38.2	
	-073.5	-38.2	
Flight 6 Profile 1	-077.0	-37.9	
	-073.5	-37.9	
Flight 6 Profile 2	-077.0	-38.0	
	-073.5	-38.0	
Flight 7 Profile 1	-077.0	-37.7	
	-073.5	-37.7	
Flight 7 Profile 2	-077.0	-37.8	
	-073.5	-37.8	
Flight 8 Profile 1	-077.0	-37.5	
	-073.5	-37.5	
Flight 8 Profile 2	-077.0	-37.6	
	-073.5	-37.6	
Flight 9 Profile 1	-077.0	-37.3	
	-073.5	-37.3	
Flight 9 Profile 2	-077.0	-37.4	
	-073.5	-37.4	
Flight 10 Profile 1	-077.0	-37.1	
	-073.5	-37.1	
Flight 10 Profile 2	-077.0	-37.2	
	-073.5	-37.2	
Flight 11	-073.7	-36.8	
	-076.8	-39.2	
	-076.8	-36.8	
	-073.7	-39.2	
	-073.7	-36.8	
Flight 12 Profile 1	-073.7	-37.0	Onshore
	-073.7	-41.0	
Flight 12 Profile 2	-073.6	-37.0	
	-073.6	-41.0	
Flight 13 Profile 1	-073.5	-37.0	
	-073.5	-41.0	
Flight 13 Profile 2	-073.4	-37.0	
	-073.4	-41.0	
Flight 14 Profile 1	-073.3	-37.0	
	-073.3	-41.0	
Flight 14 Profile 2	-073.2	-37.0	
	-073.2	-41.0	
Flight 15 Profile 1	-073.1	-37.0	
	-073.1	-41.0	
Flight 15 Profile 2	-073.0	-37.0	
	-073.0	-41.0	
Flight 16 Profile 1	-072.9	-37.0	
	-072.9	-41.0	
Flight 16 Profile 2	-072.8	-37.0	
	-072.8	-41.0	

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