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THE GEOFLOW EXPERIMENT ON ISS: EXPERIMENTAL STUDIES, PREPERATION AND EXECUTION

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Abstract

Investigations on thermal convective instabilities occurring in the spherical gap flow are of basic importance for the understanding of symmetry-breaking bifurcations during the transition to chaos. Microgravity experiments on thermal convection with a simulated central force field are important for the understanding of large scale geophysical flows, e.g., as the convective transport phenomena in the earth's liquid outer core.
We give a summary of the concurrent experimental studies for the preparation and execution of the GeoFlow experiment, which takes place at the Fluid Science Laboratory (FSL) of the International Space Station (ISS). A central symmetric force field, similar to the gravity field acting on planets, can be produced, using the effect of the dielectrophoretic force field, by applying a high voltage potential between the inner and outer sphere. The Wollaston-Shearing-Interferometry (WSI) and Schlieren technique will be used for flow visualization and to determine the expected flow pattern during the space experiment.

1 Introduction

Thermal convection in spherical shells represents an important model in fluid dynamics, astrophysics and geophysics (e.g., Busse, [1] and [2]; Busse and Riahi, [3]; Cardin and Olsen, [4], [5] and [6]; Carrigan and Busse, [7]; Cordero and Busse, [8]; Harder and Christensen, [9]; Liu et al., [10]; Roberts, [11]; Zhang, [12]). Regarding to GeoFlow recent papers were published, which describe the scientific preparatory studies, e.g. experiments development (e.g. Egbers et al., [13]), numerical simulation (Travnikov et al., [14]) and bifurcation analysis (Beltrame et al., [15]). The large scale of atmospheric flows and the convection zones of rotating stars/ planet are strongly influenced by Coriolis forces and by buoyancy forces. The resulting flow structures show a rich variety of different types of instabilities. The modes of instabilities are heavily dependent on different parameters, e.g. rotation rate, temperature gradient, gap width and material functions. Modelling such spherical gap flow experiment should help to understand phenomena, e.g. the zonal bands of Jupiter, the origin of extremely high winds in the tropics and subtropics of Saturn and Neptune, the persistent differential rotation of the Sun, the complex patterns of convection in the slowly-rotating mantle of the earth, and the rapidly rotating flows in the earth's outer core. In figure 1 a schematic cross section of the earth is shown.

Research on thermal convection with an artificial central dielectrophoretic force field under microgravity (μ-gravity) conditions are important for the comprehension of these large scale geophysical flows.
Yavorskaya et al. [17] discussed the fluid flow analogy of spherical gap flow models to atmospheric flow and convection in core regions of gaseous planets in theory. Experiments on convective flow

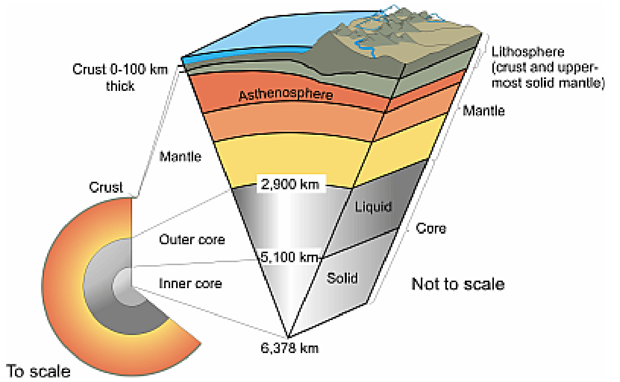

Figure 1: Schematic cross section of the earth: Thermal convective phenomena occur in the outer liquid core, structural earth's set-up from Kious and Tilling [16]

Figure 2: Science reference model (SRM) in the laboratory at BTU Cottbus

stability under μ-gravity conditions in a spherical shell system was realised by Hart et al., who did experiments on board a NASA Space Shuttle in 1985 (Hart, [18]) and in a reflight campaign in 1995 (Hart, [19]). The experiment consisted of a rotating hemispherical shell system with the possibility to apply a radial as well as a latitudinal temperature gradient in meridional direction. Gravity was simulated by applying an electrical field. The observed flow pattern were visualized with Schlieren technique and compared with 3D non-linear simulations.
The use of artificial central buoyancy force fields for simulating gravity in geophysical analogy regarding for example the liquid outer core of earth was discussed by Früh [20] and also by Beltrame [21], who concluded that the essential character of the flow is captured even if the power law of simulated artificial gravity due to central force field would not agree really with acceleration due to gravity on earth.
The GeoFlow experiment focuses on thermal-driven flows influenced by a central force field in a rotating full spherical gap model.
To eliminate the unidirectional acceleration due to gravity on earth, these long-time experiments require μ-gravity environment. As a result GeoFlow is going to take place in the FSL of Columbus module on the ISS. Launch of the GeoFlow experiment container and Columbus was at 7^{th} February 2008.

The research with GeoFlow will start in July 2008, after commissioning Columbus and FSL.
The scientific aim is, to investigate pattern formation, stability of flow states and transition to turbulence in rotating spherical ssystems. Regarding technical applications, GeoFlow is also of interest for fluid flow transport applications, e.g. pump systems. As the central force field is realised by an electro-hydrodynamic force, in particular the dielectrophoretic effect, the study can also yield new results in electro-viscous phenomena and in fluid control applications.

Since 2002, the overall preparatory research program comprised work packages as development of hardware and software as well as preliminary numerical and experimental investigations. Experiments were performed in the laboratory at BTU Cottbus using the Science Reference Model (SRM), (cf. fig. 2), and also in the laboratories of industrial partners, who built and verified the experiment hardware, using the Engineering Model (EM).
Numerical investigations and bifurcation analysis were performed by European research groups from United Kingdom, France and Germany, which are members of the GeoFlow Topical Team (cf. fig. 3). These investigation produce so much interesting results and generates new research fields, that the

Figure 3: Allocation of the GeoFlow Topical Team, industry partners and space agencies

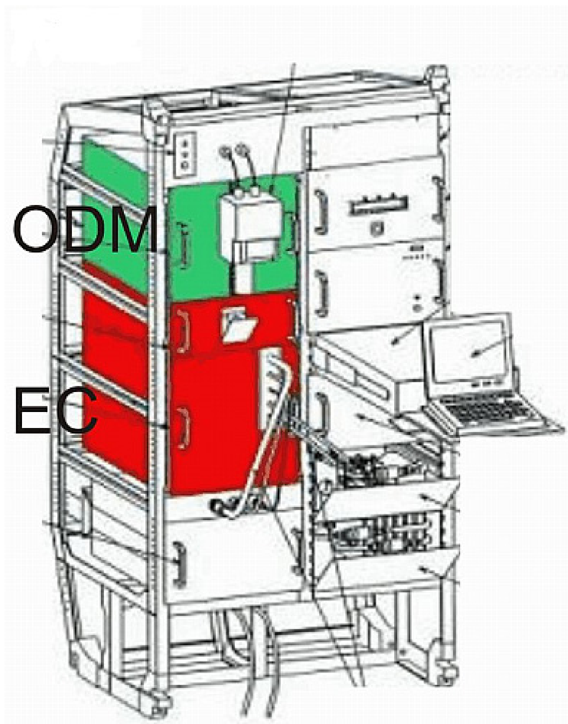

Figure 4: Schematic Fluid Science Laboratory (Image Source: ESA)

numerical work at the Topical Team partners still goes on.
These studies focus on preparation of the experiment design and on the observable parameter space by flow states simulation and on linear stability analysis and bifurcation analysis (Futterer, [22]; Travnikov, [14]; Gellert, [23]).

GeoFlow Topical Team consists of science teams from BTU Cottbus (Germany) (PI), Univerity of Potsdam (Germany), University of Leeds (U.K.), University of LeHavre (France), CIRM Marseille (France) and ESPCI Paris (France). GeoFlow is supported, in technical point of view by EADS Astrium Space Transportation GmbH Friedrichshafen (Germany), MARS Center Naples (Italy) and E-USOC Madrid (Spain). Financial and organisational support is given by the space agencies European Space Agency ESA in Noordwijk (The Netherlands) and German Aerospace Center DLR (Germany).

2 Experiment Preparation

One part of the European Columbus Orbital Facility of the ISS is the Fluid Science Laboratory (FSL). The FSL supports μ-gravity research in the field of fluid physics by means of specific triggering and observation of phenomena inside of transparent and at the surface of opaque media. It is characterised by a high level of modularity on all experiment and facility (sub-)system levels.

For the scientific fluid physics research, the FSL provides different measurement methods. While the Wollaston-Shearing Interferometry (WSI) is primarily used for the GeoFlow experiment, also the measurement methods Schlieren and Shadowgraphy can be applied.
The FSL consists of two main parts: the Central Element Module (CEM) and the Optical Diagnostics Module (ODM), (cf. fig. 4). The CEM includes a manually accessible operational area, which is

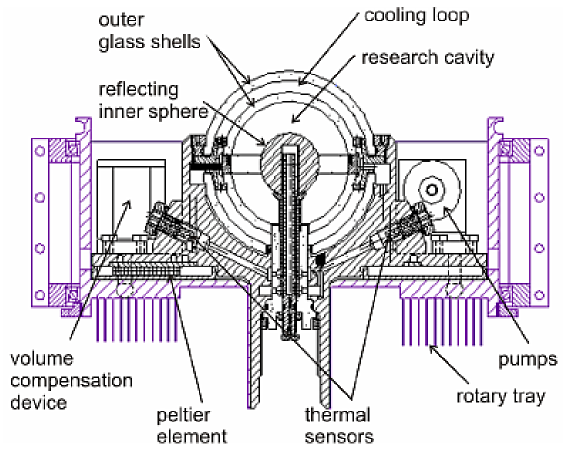

Figure 5: Schematic cross section of GeoFlow experiment cell

designed to integrate the modular experiments, which are integrated in Experiment Containers (EC).

The GeoFlow experiment hardware has been designed, on the basis of the geometrical data of the EC, which is fixed to the volume of $270 \times 280 \times 400\ mm^3$.

2.1 Experimental set-up

The experimental core consists of an inner sphere, which is made up of tungsten-carbide and two outer shells, which are made of BK7-glass (cf. fig. 5).
In the research cavity a temperature gradient is realised by uniformly heating the inner sphere and cooling the outer glass shell using temperature controlled fluid circuits filled also with silicone oil. The experiment cell is mounted on a rotating tray which allows for solid body rotation. The central force field is generated by applying a high voltage of $V_{rms} = 10\ kV$ between inner and outer sphere to generate the artificial central symmetric force field analogous to the earth's gravity field.

A low viscous silicone oil (Bayer Baysilione® M5) is used as the working fluid. Table 1 shows the properties of the working fluid, measured at $T = 25°C$, that is the average experiment environment temper-

Table 1: Experiment parameters

Geometric parameters	
Inner radius r_i	$13.5\ mm$
Outer radius r_o	$27.0\ mm$
Gap width $d = r_o - r_i$	$13.5\ mm$
Radius ratio $\eta = r_i/r_o$	0.5
Aspect ratio $\beta = (r_o - r_i)/r_i$	1.0
Variable experiment parameter	
Rotation rate Ω	$0 - 2\ Hz$
High voltage V_{rms}	$0 - 10\ kV$
Temperature difference ΔT	$0 - 10\ K$
Physical proberties of the working fluid ($T = 25°C$)	
Type	Silicone oil
Density ρ	$920\ kg \cdot m^{-3}$
Kinematic viscosity ν	$5 \cdot 10^{-6}\ m^2 \cdot s^{-1}$
Thermal conductivity λ	$0.116\ W \cdot K^{-1} \cdot m^{-1}$
Thermal diffusivity κ	$7.735 \cdot 10^{-8}\ m^2 \cdot s^{-1}$
Cubic exp. coeff. α	$108 \cdot 10^{-5}\ K^{-1}$
Dielectric constant ε_r	2.7
Therm. coeff. of ε_r	$1.07 \cdot 10^{-3}\ K^{-1}$
Dimensionless parameters	
Taylor number Ta	$Ta \leq 1.3 \cdot 10^7$
Central Rayleigh number $Ra_{central}$	$Ra_{central} \leq 1.4 \cdot 10^5$
Prandtl number Pr	$Pr = 64.64$

ature. In particular, in the expected environment temperature range, which is approx. $20 - 35°C$, differences in physical properties from the given values are negligible. However, temperatures of the in- and outflow of the cooling and heating loops are measured permanently and differences of the parameters set will be considered in the data analysis. While the Coloumb force does not affect fluid due to high frequency alternation, the dielectrophoretic effect results in central force field and acts as ponderomotive force due to the inhomogeneous electrical field.

Regarding dimensionless parameters, the Taylor number Ta is proportional to the rotation rate Ω, $Ta \sim \Omega^2$.

$$Ta = \left(\frac{2\Omega d^2}{\nu}\right)^2 \quad (1)$$

While in natural convection phenomena, the

Rayleigh number Ra often denotes the temperature difference.

(2) $$Ra = \frac{\alpha \Delta T g d^3}{\nu\kappa}.$$

This parameter is called the central Rayleigh number $Ra_{central}$ which is proportional not only to the temperature gradient ΔT in the spherical gap but also to the acceleration due to the central force field g_E, $Ra_{central} \sim (\Delta T \cdot g_e)$.

(3) $$Ra_{central} = \frac{\gamma \Delta T g_e d^3}{\nu\kappa}$$

As g_e is proportional to $V_{rms}^2 \cdot r^{-5}$, it follows that $Ra_{central} \sim \Delta T \cdot V_{rms}^2 \cdot r^{-5}$. While acceleration due to gravity is approx. $10m/s^2$ on earth's surface, the largest value of acceleration due to high voltage field is approx. $10^{-1}m \cdot s^{-2}$ at $r = r_o$, r_o as outer radius of the research cavity, and $V_{rms} = 10kV$.

(4) $$g_e = \frac{2\varepsilon_0\varepsilon_r}{\rho} \cdot \frac{r_o^2}{\beta^2 r^5} \cdot V_{rms}^2,$$

The Prandtl number Pr reflects physical properties of the working fluid.

(5) $$Pr = \frac{\nu}{\kappa}$$

Regarding convection in laboratory on earth, superimposed with central artificial force field, both Rayleigh numbers have to be considered. For the μ-gravity environment at ISS only $Ra_{central}$ is neccessary.

3 Measurement Methods

For the first phase of GeoFlow on-orbit operations, measurements of the flow field are therefore done using the Wollaston-Shearing-Interferometry (WSI). As mentioned earlier, Schlieren technique and Shadowgraphy was implemented within FSL and can be applied, too. Due to experiment constraints, measurement techniques are used in reflection mode. The inner sphere of the set-up is prepared to act as a mirror. Figure 6 shows a sketch of the WSI set-up at BTU laboratory used for preparatory

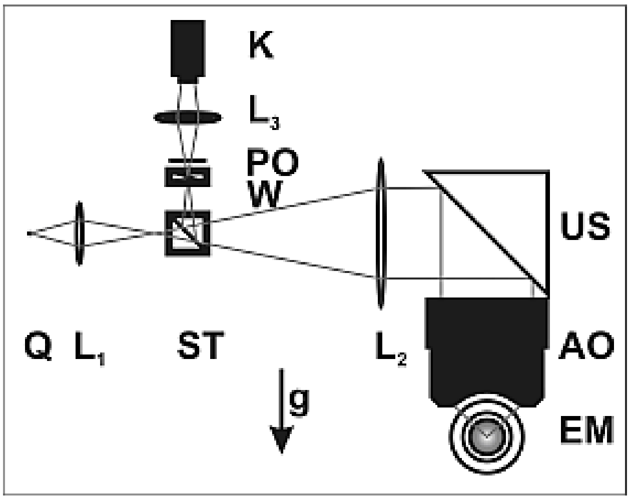

Figure 6: Sketch of the WSI set-up at BTU-Laboratory. Laser (Q), Lens (L), Beam Separation (ST), 90° mirror (US), Adaption Optics (AO), Science Reference Model (EM), Wollaston prism (W), Polarisator (PO), CCD Camera (K), gravity (g) vector

experimental works. Because of the acceleration due to gravity, the operation mode on earth is parallel to the axis of the gravitational force g on earth.
The Adaption Optics (AO) includes an optical lens tool which converts the planar waves emitted by the Laser (Q) into spherical waves and the reflected waves vice versa. This is needed due to the spherical geometry of the experiment shell system. The 90° mirror (US) deflects the beams to the AO, which focus the waves to the centre of the experiment cell (EM). The beam separation cube (ST) deflects the reflected beams, coming from the AO, to the Wollaston Prism (W) and the Polarisator (PO).

The WSI method detects refractive index gradients of the working fluid and is therefore sensitive to density gradients caused by temperature differences in the GeoFlow experiment. Optical path length variations results in interference phenomena which are directly photographed by a CCD camera (K). Figure 7 shows WSI images from ground test sequences taken at different parameter points. Note

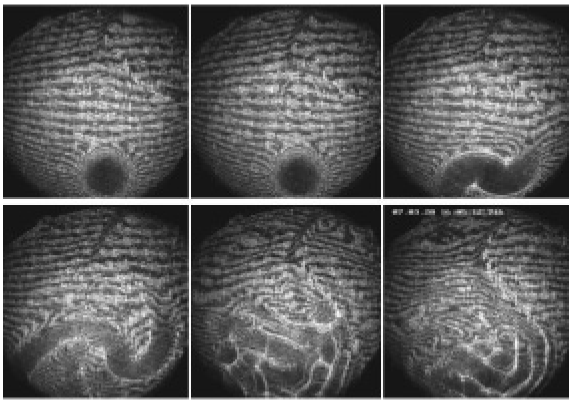

Figure 7: Natural Convection ($V_{rms} = 0kV$). WSI images taken at constant Rayleigh number $Ra = 4.31 \cdot 10^6$ and increasing Taylor numbers (from left to right anf top to bottom: $Ta = 0$, $Ta = 8.6 \cdot 10^2$, $Ta = 1.3 \cdot 10^5$, $Ta = 5.4 \cdot 10^5$, $Ta = 1.1 \cdot 10^7$, $Ta = 1.3 \cdot 10^7$

the complicated interferogram structures at large Taylor numbers.

4 Experimental Phase

4.1 Experiment flow plan

The on-orbit experiment flow plan is based on preparatory numerical work. Since the high voltage will be set-up to a constant value of $10kV$, free parameters are the temperature difference ($Ra_{central}$) and the rotation rate (Ta). The expected experiment duration time of several weeks allows for a high resolution parameter scan, (cf. fig. 8).

Main part of the first experiment run is the investigation of flow patterns at rotation rate $\Omega = 0Hz$, i.e. varying only the temperature difference without rotation. After this, superposition of rotation will be set-up. The experiment flow plan can be divided into no-rotation, e.g. $\Omega = 0Hz$, low rotation cases with $\Omega = 0.008 - 0.16Hz$ with a step width of $0.008Hz$, medium rotation cases with $\Omega = 0.2 - 1.0Hz$ with a step width of $0.2Hz$ and high rotation cases with $\Omega = 1.2 - 2.0Hz$ also with a step width of $0.2Hz$. The temperature difference between inner sphere

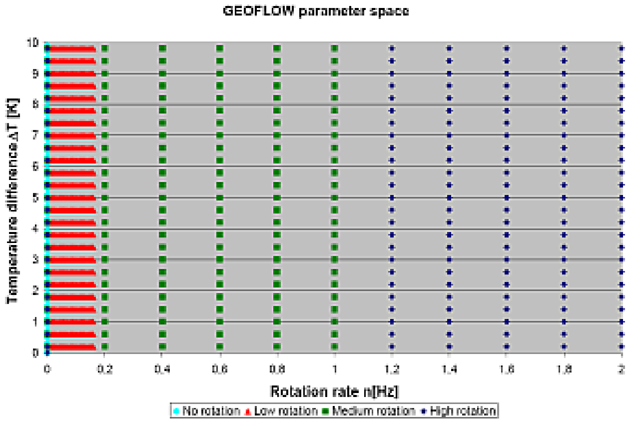

Figure 8: Sketch of high resolution parameter scan. Symbols are explained within the figure

and the inner glass shell varies from $\Delta T = 0K$ up to $\Delta T = 10K$ with a step width of $0.2K$.
To investigate the dependence of solutions on initial conditions some experiment sequences will start applying e.g. with a fixed temperature difference while in other experiments ΔT will be increased smoothly. In a preliminary experimental study, we found special tracer particles to be in principal suitable for quantitative flow field measurements under the given experiment conditions, e.g. using Laser Doppler Velocimetry. Here, the high voltage field was defined to be the most critical parameter as it has the potential to deflect the movement of the particles relative to the fluid flow field which would then have an influence on those measurements. Several additional tests, e.g. due to crew safety, are necessary to make these particles acceptable for space research and to perform particle loaded fluid flow experiments in future GeoFlow campaigns.

4.2 Data transfer and data storage

The GeoFlow experiment is a fully automated stand alone experiment and could run without any manpower of the astronauts on ISS, excepted starting up. The specified Experiment Procedures (EPs) were programmed by the User Support and Operations Centre in Madrid, Spain (E-USOC). The hard-

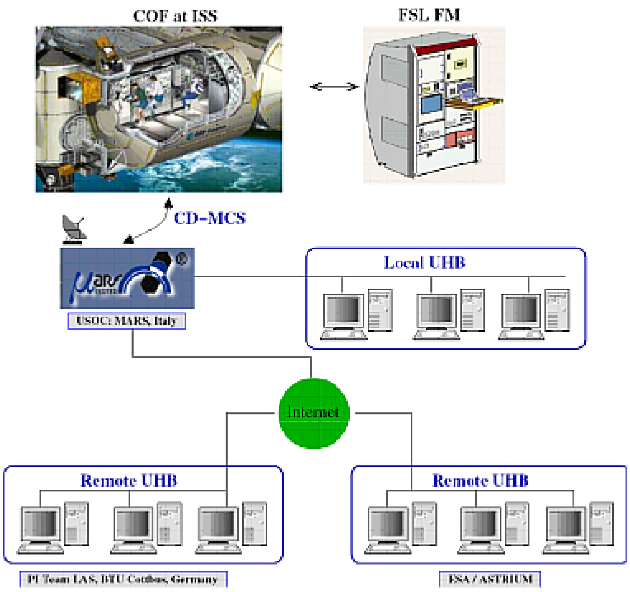

Figure 9: GeoFlow data flow

ware support for the GeoFlow experiment is given by EADS Astrium in Friedrichshafen, Germany. The support for the Fluid Science Laboratory is given by the MARS Centre in Naples, Italy. The data flow with the GeoFlow Experiment is shown in figure 9.

The downlink of the image data is controlled by the MARS Centre in Naples, that distributes the data to the specified centres. The data storage at BTU is calculated to $4000GB$, including backup, analysis and interpretation of data.

5 Outlook

While the first GeoFlow campaign will probably be finished till November of 2008, reflight possibilities are under discussion yet. First consideration comprises the variation of experiment fluid's viscosity to a higher viscous and more temperature dependent fluid would lead the physical model to convection in the earth's mantle. Second idea is to vary the gap width to a narrower spherical gap, which leads to the earth's atmospheres conditions and for the third possibility, it is discussed to change the geometry from the spherical gap to a cylindrical gap. This would allow for investigations of fluid flow with technical application, for e.g. heat exchangers, pumps and micro-dosing systems, as well as such a geometry in basic research, e.g. Couette-Taylor flows.

6 Acknowledgements

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