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Microgravity Science on International Space Station (ISS): The GeoFlow Experiment

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Kurzfassung

Die experimentelle Untersuchung der thermischen Konvektion im rotierenden Kugelspalt unter dem Einfluss eines künstlich aufgebauten Zentralkraftfeldes ist Thema des Mikrogravitationsexperimentes GeoFlow, das im Fluid Science Laboratory (FSL) der Internationalen Raumstation (ISS) betrieben werden soll. Im Rahmen eines von der europäischen Raumfahrtagentur (ESA) geförderten Topical Team werden mit nationalen und internationalen Partnern (F. Feudel, Universität Potsdam; L. Tuckerman, LIMSI Paris; P. Chossat, CIRM Marseille, R. Hollerbach, Universität Leeds) unter Federführung des BTU-Lehrstuhls für Aerodynamik und Strömungslehre verschiedene Arbeitspakete zur numerischen Vorhersage, Analyse und Interpretation derartiger geophysikalisch motivierter Strömungen bearbeitet. Am Lehrstuhl werden, gefördert durch das Deutsche Zentrum für Luft und Raumfahrt e.V. (DLR), insbesondere begleitende dreidimensionale numerische Untersuchungen dieses sphärischen Rayleigh-Bénard Problems unter Einfluss einer dielektrophoretischen Kraft für einen weiten Parameterraum der Rayleigh- und Taylor- Zahl durchgeführt und hier vorgestellt. Ein begleitendes Laborexperiment an der BTU (Science Reference Model) und weitere ergänzende numerische Simulationen dienen der wissenschaftlichen Vorbereitung des Raumstationsexperimentes, welches im Herbst 2007 mit dem europäischen Weltraumlabor Columbus auf die ISS transportiert wird.

Abstract

We present numerical and experimental preliminary studies for a microgravity experiment on thermal convection in rotating spherical shells named GeoFlow, which will be integrated at Fluid Science Laboratory FSL of International Space Station ISS. Numerical studies of this spherical Rayleigh-Bénard problem under a central dielectrophoretic force in microgravity environment are accomplished for a wide range of Rayleigh and Taylor number. For testing GeoFlow framework a laboratory experiment is designed, constructed and tested including set-up of optical measurement techniques as Wollaston shearing interferometry.

1 Introduction

Modelling of large scale geophysical flow, like convection in the Earth's outer core, can be done regarding fluid flow between concentric spherical shells (Fig. 1). Focusing on main acting forces in the inner Earth, that is temperature gradients and rotation, and neglecting magnetic effects in order to simplify the problem, that corresponds to research on stability and pattern formation of thermal convection in a rotating spherical gap.

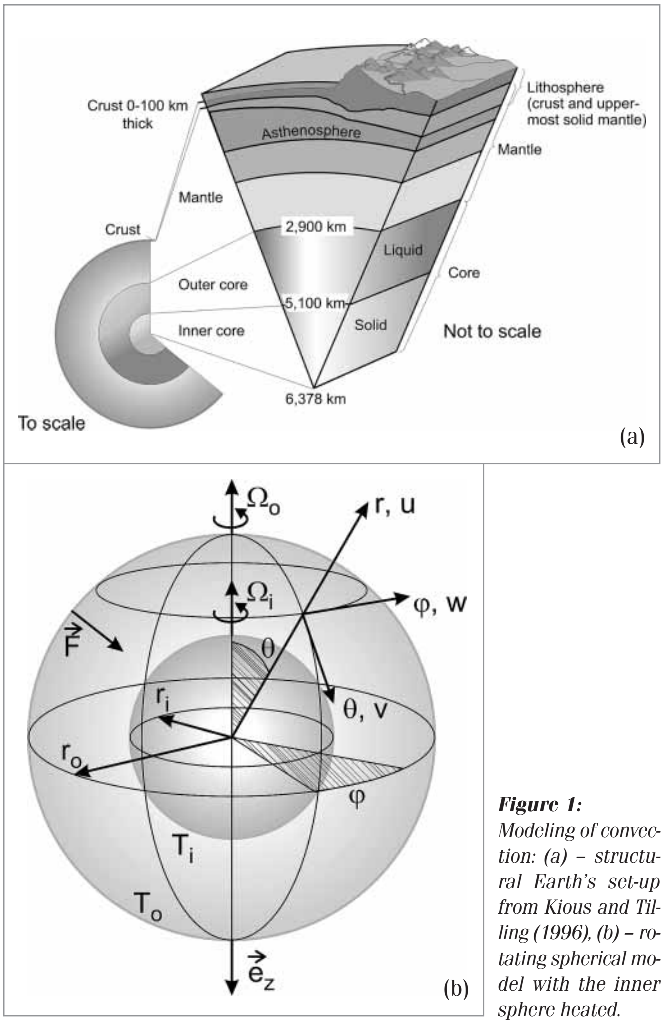


Figure 1: *Modeling of convection: (a) – structural Earth's set-up from Kious and Tilling (1996), (b) – rotating spherical model with the inner sphere heated.*

If phenomena are studied experimentally in an Earth lab, gravity acts axial to a spherical model, and not central, like in the Earth's core. Such a central force field can be setup using the dielectrophoretic effect by applying a high voltage alternating field on the inner sphere which is than acting as a spherical capacitor (YAVORSKAYA et al., 1984; HART et al., 1986; EGBERS et al., 1999). A minimum of resulting artificial central acceleration amounts to approximately 10^{-3} m/s², showing that acceleration due to gravity with $g \approx 10$ m/s² will always be dominant on Earth. Necessary microgravity conditions for research, especially required long-term ones (EGBERS et al., 1993, 1996), are available at the International Space Station (ISS). In particular within the Fluid Science Laboratory (FSL), part of coming European Columbus module on ISS (Fig. 2), an experimental container named GeoFlow is planned, containing such a spherical shell model for long-term investigation of thermal convection in rotating spherical shells under the influence of a central force field (ESA, 2005; EGBERS et al., 2003; TRAVNIKOV et al., 2003; BELTRAME and EGBERS, 2003).

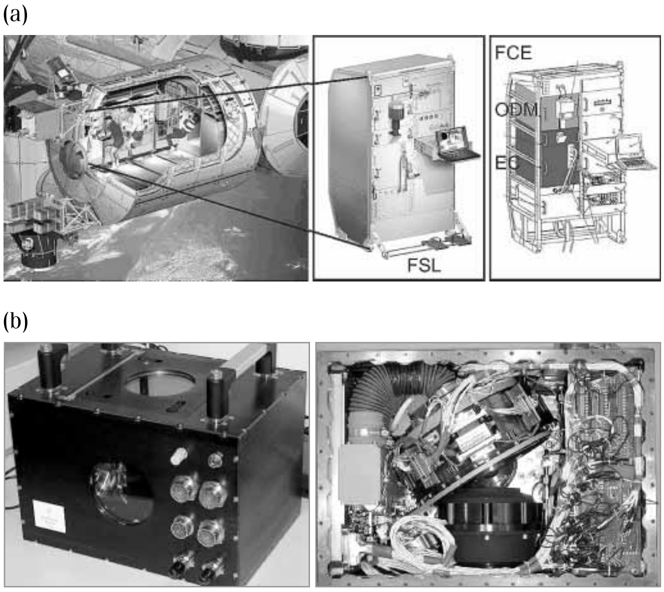


Figure 2:
Microgravity science at International Space Station (ISS): (a) – Fluid Science Laboratory (FSL) at European Columbus module of ISS, (ESA, 2005). Within this modular set-up a Facility Core Element (FCE) involves an Experiment Container (EC), Optical Diagnostics Module (ODM) provides measurement methods. (b) – EC itself and integration of fluid cell assembly, adaption optics and power control (under license of EADS Astrium.

Numerical studies are used for preparation of experimental design and complementary parameter variations as well as analysis of flow stability. At lab a preproduction experiment is setup to study technical and scientific requirements which are also accompanied by numerical calculations. Below we will present state of work within some part of these topics. In the first part we present equations and non-dimensional parameters introducing physical basics of convection in spherical shells under influence of central force field set-up by a high voltage field. Numerical method and experimental constraints will be mentioned shortly. The second part will then show results of numerical simulation we have done for space lab environment corresponding to thermal convection in rotating spherical shells with a pure central force field. The third part will show set-up of a preproduction model of planned space lab experiment. Here we will present some thermal tests focusing on testing the optical diagnostics.

2 Physical Model

2.1 Governing Equations

Scaling length by the difference between inner and outer radius $d = (r_o - r_i)$, time by the thermal diffusive timescale $\tau_{th} = d^2/\kappa$, velocity $\mathbf{U}$ by κ/d, and temperature T by the imposed temperature difference $\Delta T = T_i - T_o$, nondimensional equations in Boussinesq approximation become

$$\nabla \cdot U = 0, \tag{1}$$

$$\mathrm{Pr}^{-1}\left[\frac{\partial \mathbf{U}}{\partial t} + \left(\mathbf{U}\cdot\nabla\right)\mathbf{U}\right] = -\nabla p + \nabla^2\mathbf{U} + \mathrm{Ra}T\hat{e}_z + \mathrm{Ra}_{centr}T\hat{e}_r + \sqrt{\mathrm{Ta}}\hat{e}_z \times \mathbf{U} + \tilde{\mathrm{R}}\mathrm{a}Tr\sin\theta\hat{e}_{eq} \tag{2}$$

$$\frac{\partial T}{\partial t} + \left(\mathbf{U}\cdot\nabla\right)T = \nabla^2 T\ . \tag{3}$$

Here the system is rotating with constant rotational frequency $N = \Omega/(2\Pi)$. Then the Prandtl number

$$\mathrm{Pr} = \frac{\nu}{\kappa} \tag{4}$$

is a material property of the fluid, and the Rayleigh number measures the imposed thermal forcing. Natural convection in an axial force field in lab is described by

$$\mathrm{Ra} = \frac{\alpha \Delta T g d^3}{\nu\kappa}\ . \tag{5}$$

Here ν and κ are the fluid's viscosity and thermal diffusivity, respectively, α is the thermal expansion coeffient, and g is acceleration due to gravity, with $-\hat{e}_z$ denoting its direction, vertically downward. For an artificial force field set-up by dielectrophoretic force an additional central Rayleigh number describes the thermal convection in central force field

$$\mathrm{Ra}_{centr} = \frac{\gamma \Delta T g_e d^3}{\nu\kappa}\ . \tag{6}$$

Here γ is the dielectric variability and g_e the electric acceleration due to electrohydrodynamic force with

$$g_e = \frac{2\varepsilon_0\varepsilon_r}{p}\cdot\frac{r_o^2}{\beta^2 r^5}\cdot V_{rms}^2$$

where $\in_0$ and $\in_r$ correspond to dielectric constant and relative dielectric number, ρ is the density and V_{rms} the high voltage alternating electrical field giving the central force. The geometry factors reveal different parameter value at the inner or the outer sphere when referred to inner or outer radius, respectively. It is expedient to name the Rayleigh number related to outer radius which is smaller. Note also the fact that resulting central force is proportional to $1/r^5$. Nevertheless see TRAVNIKOV et al. (2003) and TRAVNIKOV (2004) for analysis of rich dynamics.

Rotational effects are treated in Coriolis and centrifugal forces, described by Taylor number

$$\mathrm{Ta} = \left(\frac{2\Omega d^2}{\nu} \right)^2 \tag{7}$$

and the additional factor

$$\tilde{\mathrm{R}}\mathrm{a} = \frac{\alpha \Delta T}{4} \mathrm{Pr}\,\mathrm{Ta}, \tag{8}$$

with e_{eq} as unit vector in equatorial plane.

2.2 Boundary Conditions

The boundary conditions associated with (2) are no-slip for **U**

$$\mathbf{U} = 0 \quad \text{at} \quad r = r_i, r_o, \quad (9)$$

and for (3) they are

$$\begin{aligned} T &= 1 \quad \text{at} \quad r = r_i, \\ T &= 0 \quad \text{at} \quad r = r_o, \end{aligned} \tag{10}$$

corresponding to inner heating and outer cooling of spherical shells. Regarding convection in lab both Rayleigh numbers has to be considered. For the microgravity environment at ISS only $\mathrm{Ra}_{central}$ is necessary.

2.3 Numerical Method

This system of equations and boundary conditions is solved using the numerical code of Hollerbach (2000), in which **U** and T are expanded in terms of Chebyshev polynomials in r, and Legendre functions in θ and φ. Resolutions as large as 30×20×30 for **U** and T were used. Within this simulation work it is convenient to refer the Rayleigh number to outer radius ratio and also to scale the equations with r_o. Then Ra_{centr} can be written without geometry. In the following the denoted Rayleigh number is defined as $\mathrm{Ra}_{centr} = (2\in_r \in_r \gamma)/(\rho\nu\kappa) \cdot \Delta T V^2_{rms}$, showing that for the experiment temperature difference ΔT and high voltage V_{rms} are the parameters which give the drive for convection.

2.4 Experimental Constraints

Further values for the calculations come along with experimental constraints. So working fluid, filling the spherical gap, is a silicone oil of GE Bayer Silicones, having a Prandtl number Pr = 64.64. With the inner radius r_i = 27 mm and outer radius r_o = 54 mm the radius ratio gets $\eta = 0.5$. To reach small Rayleigh numbers a possible experiment plan includes applying a constant ΔT = 10 K and varying the voltage V_{rms} up to 10 kV, Rayleigh number than reaches $\mathrm{Ra}_{centr} \leq 1.4 \cdot 10^5$. A possible rotation rate up to 2 Hz results in Taylor number $\mathrm{Ta}_{max} = 1.3 \cdot 10^7$.

3 Simulation Results

Fig. 3 shows which type of solution exists in different parts of the (Ra_{centr}, Ta) parameter space. Analogue to stability analysis for the rotating case the most unstable mode depends on Taylor number (TRAVNIKOV, 2004). It is m = 4 for lower Ta. Above $\mathrm{Ta} \approx 4 \cdot 10^4$ mode of steady convection changes to m = 5. Above linear stability steady convection occurs with constant energy of system for every mode. Increasing Rayleigh number reveals periodic time-dependent solutions with keeping spacial structure of convection. Quasi-periodic solutions are found only for two single parameter sets. Transition to irregular behaviour arises in a narrow range of Rayleigh number. Analysis of spatial structure is not finished yet, but spatious scales are kept, so that term of turbulence is not used here.

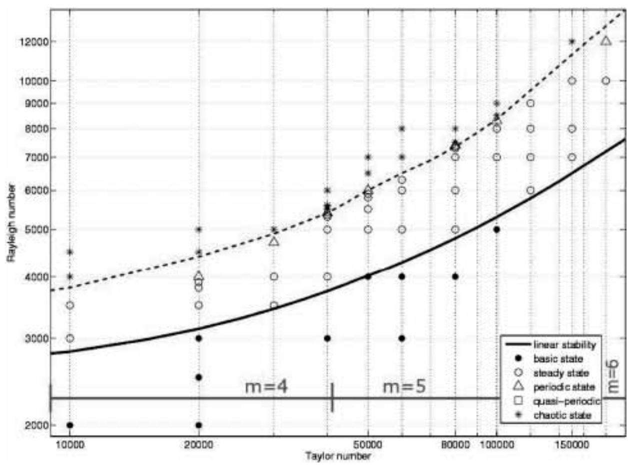


Figure 3:
Overview of convective states in spherical shells of η = 0.5 for Pr = 64.64 depending on Ra_{centr} and Ta: Besides types of solutions (characterized in rotating frame of references) diagram show linear stability (solid) and critical line (dashed), where time-dependent solution gets irregular. Additionally region of linear most unstable mode m is marked (GELLERT et al., 2005).

Fig. 4 and Fig. 5 show examples of fluid flow for the non-rotating and rotating case, respectively. For Taylor number Ta = 0 the most unstable mode is m = 4, again according to stability analysis. Nevertheless axisymmetric solution seems to exist, too. That mode m = 0 accurs selfcontained and not as a mode competition within the numerical calculation of that parameter set-up. Further planned studies on influence of start solution and use of path following methods can analyse stability in more detail. For rotation Ta ≠ 0 mode of steady convection changes to m = 5.

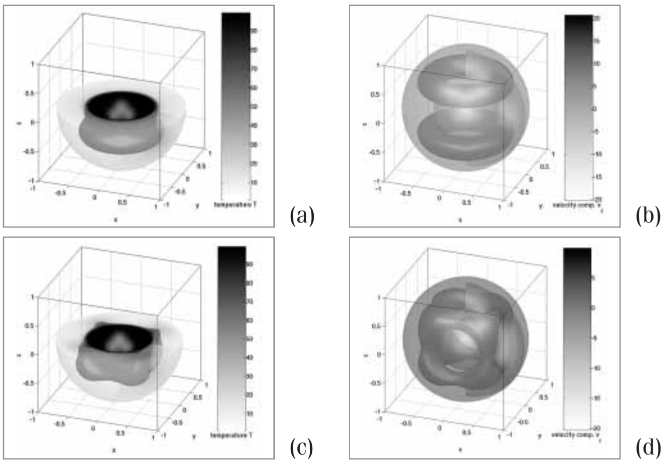


Figure 4:
Convection for the non-rotating case Ta = 0, $Ra_{centr} = 4 \cdot 10^3$. Upper row: Axisymmetric convective flow of mode m = 0: (a) – temperature field, (b) – radial velocity component. Lower row: Steady state convection of mode m = 4: (c) – temperature field, (d) – radial velocity component. Temperature field is visualized only in southern hemispherical shell and given in procent of T_{max}. Velocity component, visualized over the whole gap, points out the symmetry to equatorial plane. Arbitrarily chosen value of isosurface of T and U, resp. is highlighted.

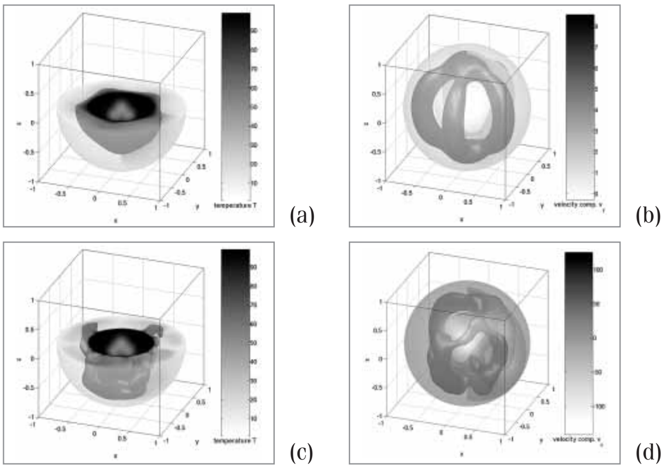


Figure 5:
Convection for the rotating case Ta ≠ 0. Upper row: Steady state convection of mode m = 5 (Ta = $4 \cdot 10^4$, $Ra_{centr} = 4 \cdot 10^3$): (a) – temperature field, (b) – radial velocity component. Lower row: Chaotic convection (Ta = $8 \cdot 10^4$, $Ra_{centr} = 5 \cdot 10^4$): (c) – temperature field, (d) – radial velocity component. Display of data follows description in Fig. 4.

4 Collateral Lab Research

Fig. 6 shows design of preproduction experimental set-up. In principle separated heating and cooling loops allow uniform set-up of thermal gradients in research cavity. Peltier elements heat and cool, respectively, and pumps provide for recirculation of heating and cooling fluid. Volume compensation devices balance expansion and contradiction due to thermal working of fluids in the loops. For applying a high voltage field inner spherical sphere is made of tungsten carbide and inner boundary of outer glass shell system touching research cavity is coated with indium tin oxyde (ITO). Rotation is done by belt transmission of a rotary tray.

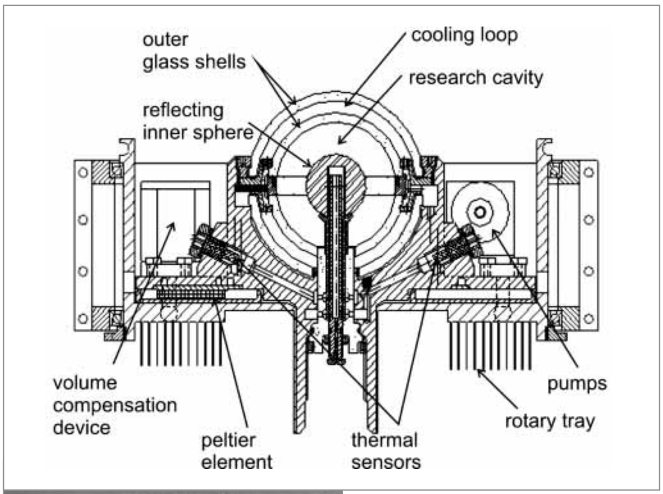


Figure 6:
GeoFlow Breadboard

Operating tests are done in the following sequence. Hereby basic convection phenomena is ranked first. Than influences like rotation and artificial force are switched on:

- Set-up of thermal gradients
  - stability of natural convection
  - parameter ΔT resp. Ra
- Rotation of spherical shell
  - influence of rotation
  - parameter N resp. Ta
- Set-up of high voltage field
  - influence of artificial central force field
  - parameter V_{rms} resp. Ra_{centr}
- Use of different fluids
  - influence of material
  - parameter ν resp. Pr

Fig. 7 gives the principle of set-up Wollaston shearing interferometry as used measurement method. It shows a modular Wollaston shearing interferometer which also works as Schlieren and shadowgraphy by changing only the optical component in focal point of lense L_2, which is Wollaston prism, cutting edge or just nothing, respectively. Basically the optics detect refractive index gradients, which are sensitive for temperature and therefore density gradients. This results in variation of optical path length, giving intereference phenomena. If only resulting beam deflection is visualized, Schlieren and shadowgraphy technique can be used. Further details are described in FUTTERER (2006) and HUSCHTO (2006).

Testing set-up of thermal gradients is done by using the optics as Wollaston shearing interferometer. Than for no gradient (ΔT = 0 K), theoretically one expects parallel fringes in a reference picture. Fig. 8 (a) shows a reference image with curved fringes which is due to spherical geometry of measuring section through spherical shell. Setup of thermal gradients will then move the fringes or even create new ones. Example of resulting interferograms for two moderate thermal gradients of ΔT = 1.7 K and ΔT = 3.5 K are shown in Fig. 8 (b) and Fig. 8 (c), respectively. A more detailed analysis on stability of structure and interpretation of interferogram is projected considering numerical calculations (FUTTERER et al., 2004, 2005). First results here show transient convection before stable state convection which than could compared with numerical results for that case of natural convection in spherical shells without rotation and high voltage field in Earth lab.

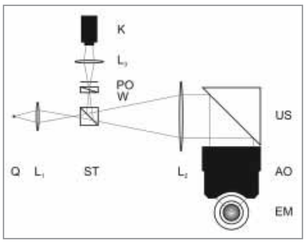
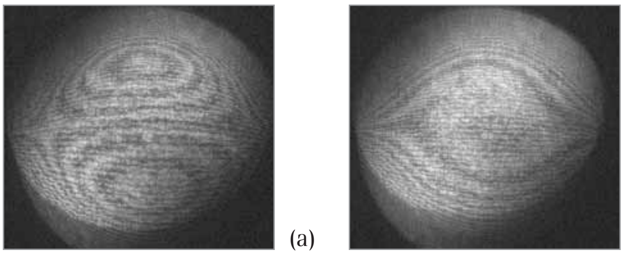


Figure 7:
Optical set-up of modular Wollaston shearing interferometer: light source Q, a diode amplified laser having a power of 10 mW, sends rays of wavelength λ= 532 nm, which is widened via lenses L_1 and L_2 and focused on center of spherical shell model EM via mirror US and adaption optics AO. Reflecting inner sphere sends it back and at last it is turned round by beam splitter ST through Wollaston prism W and polarizer PO, focused with lense L_3 at CCD ship of FireWire camera K.


(a) (b)

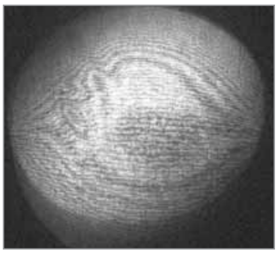

(c)

Figure 8:
Testing set-up of thermal gradients:
(a) Ti = 19.4C, To = 19.4C ! T = 0 K,
(b) Ti = 25.3C, To = 23.6C ! T = 1.7 K,
(c) Ti = 30.3C, To = 26.8C ! T = 3.5 K.

5 Outlook

We presented numerical and experimental preliminary studies for a microgravity experiment on thermal convection in rotating spherical shells named GeoFlow, which will be integrated at Fluid Science Laboratory FSL of International Space Station ISS. In the first part we talked about physical basics of convection in spherical shells under influence of central force field set-up by a high voltage field. The second part showed rich dynamics of numerical simulation and the third part provided a preproduction model of planned space lab experiment with first results of thermal tests focusing on measurement method of Wollaston shearing interferometry.

Next steps for numerical simulation of spherical Rayleigh-Bénard problem under a central dielectrophoretic force in microgravity environment are research on nature of mode interactions with method of path following and transition to turbulence. Within the accompanying lab experiment work further experimental and numerical research has to be done. That is the commissioning of thermal tests which then come along with the experimental investigation and numerical simulation of natural convection in spherical shells. An important scope will be the evaluation of a data interpretation method for Wollaston shearing interferometry with simulated data.

Actual planning for time schedule is having first flight campaign supposed to take place in 2007. Then control of experiment will also be at Cottbus. The communication centre MARS, Naples, Italy, uses the Decentralized Monitoring und Control Subsystem (CD-MCS) for communication with Columbus which allows on-line monitoring of measurements. BTU scientists will be connected via grafical user interface (UHB), as well as industrial partner EADS Astrium (Fig. 9).

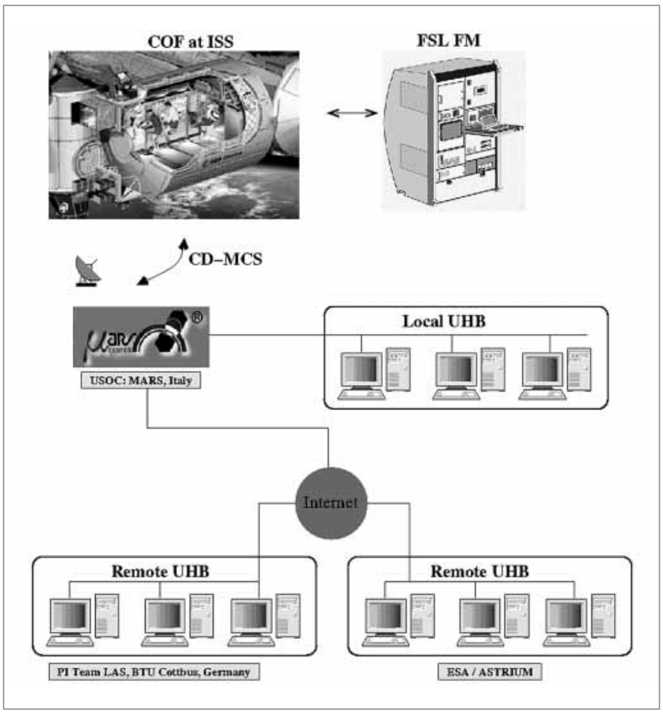


Figure 9:
Cascaded communication during experiment runs: COF – Comlumbus Orbital Facility, USOC – User Support and Operations Centre, CD-MCS – Decentralized Monitoring und Control Subsystem, UHB – User Home Base.

Acknowledgement

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