The Use of Microaccelerations Data for Convection Modeling & Analysis of the Microaccelerations Limits

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6. Tutorial of the basic system & the use of the microaccelerations in space flight

NOMENCLATURE

Nu	Nusselt number, $qL/\lambda\Delta T$
ε	$= (T-T_C)/T_C$
Ra	Rayleigh number, $g\beta_T\Delta TL^3/\nu a$
Ra_V	vibrational Rayleigh number
Ra_Ω	rotational Rayleigh number
q	heat flux
λ	thermal conductivity
T_C	critical temperatute
β_T	coefficient of volume expansion
ν	kinematic viscosity
a	thermal diffusivity
Q_X, Q_Y	temperature differences
Pr	Prandtl number, ν/a
Sc	Schmidt number, ν/D
D	coefficient of diffusion

COMGA COnvection in MicroGravity and Applications

GOALS & TASKS OF THE PROJECT "CRIT" on ISS

- Experimental study of the basic characteristics of convection & heat transfer processes in the near critical fluid in controlled microgravity environment and heat supply to the boundary

$$\mathbf{Nu = f(\varepsilon, Ra, Ra_V, Ra_\Omega)}$$

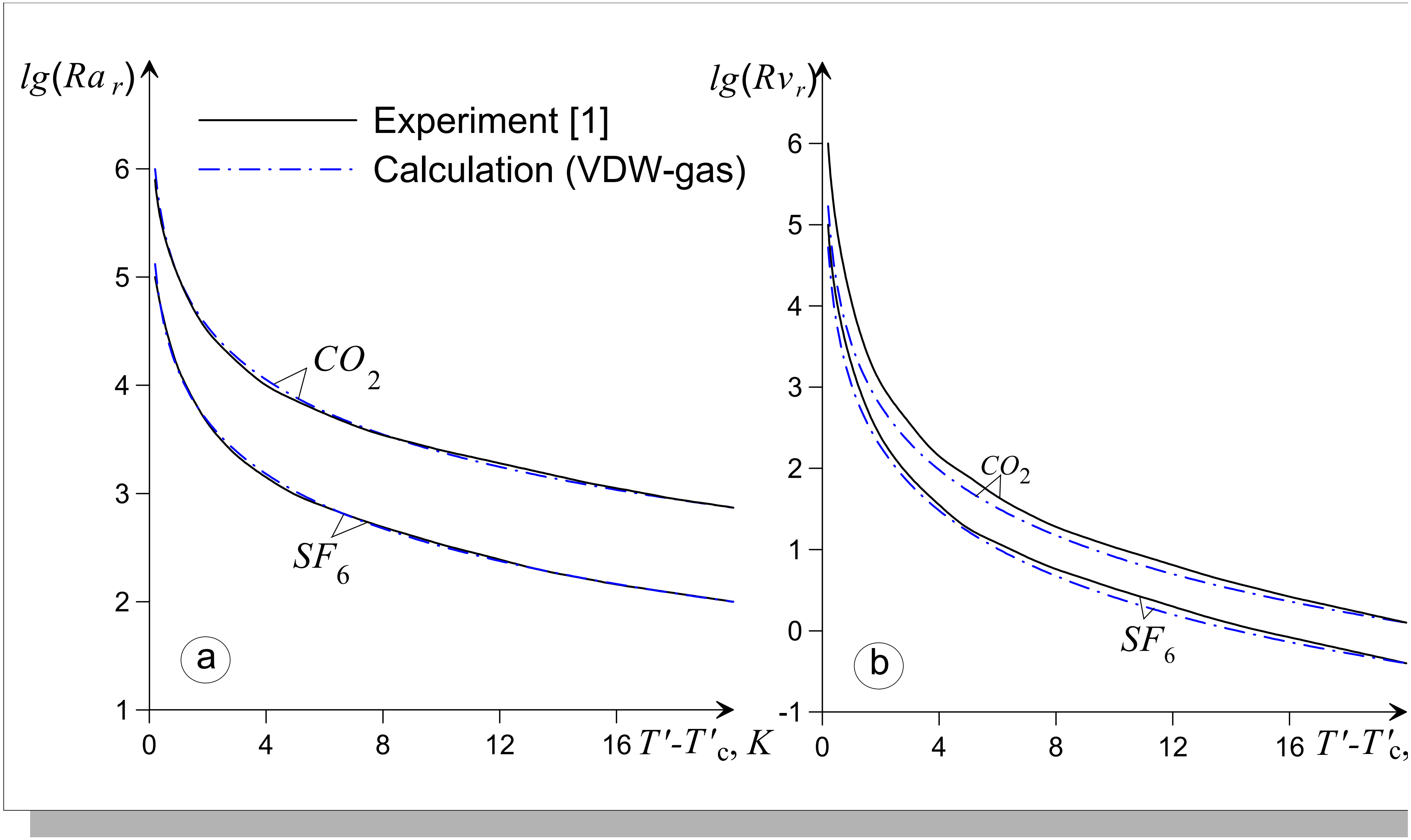
- Study of the impact of characteristics microgravity components in space flight on convection

- Measurements of the nongravitational mechanisms of the isothermal and non isothermal wave and near ctitical flows in controlled microaccelerations regime

- Study of the requirements for microacelerations for precise measurements of the physical properties close to the critical point in microgravity

- Tests of the mathematical models of compressible nonperfect gas

- Near critical sensor of the microgravity environment



Experimental and calculated Rayleigh (Ra_r) and vibrational Rayleigh (Rv_r) numbers as a functions of reduced temperature

(a) ALICE-2 instrument and convection sensor DACON (top) onboard Mir. Kosmonaut S.V. Avdeev vibrates the instrument. (b) An example of heat propagation under vibration (1.6 Hz)

MICROACCELERATIONS CALCULATION OF QUASI-STEADY ACCELERATIONS

Microacceleration, **n,** in a point at a distance**, r,** from the center of mass of the satellite in orbital flight :

$$\mathbf{n} = \mathbf{r} \times \frac{d\boldsymbol{\omega}}{dt} + (\boldsymbol{\omega} \times \mathbf{r}) \times \boldsymbol{\omega} + \frac{\mu_e}{|\mathbf{R}|^3}\left[\frac{3(\mathbf{R}\cdot\mathbf{r})\mathbf{R}}{|\mathbf{R}|^2} - \mathbf{r}\right] + \frac{F}{m}, \qquad (1)$$

here **ω** - absolute angular velocity of satellite as a solid body, μ_e - gravity parameter of the Earth, **R** - vector of the geocentric distance (center of mass), **F** - vector of the nongravity forces, **m** – mass.

Microaccelerations regimes:

- **Limiting case of** zero gravirty **(weightlessness) -** n = 0,
- Low gravity **regime** n/go= << 1**,** $\mathbf{g_o}$ **- acceleration on the Earth**
- **Generalized low gravity approach** (effective gravity) **with zero angular acceleration**

Mathematical Model and Governing Equations

-Three-dimensional unsteady Navier – Stokes equations in space flight
- Heat and mass transfer equations
- Quasi-steady microaccelerations

$$\frac{\partial u}{\partial t}+(u\nabla)u+2(\Omega\times u)=\nu\Delta u-$$

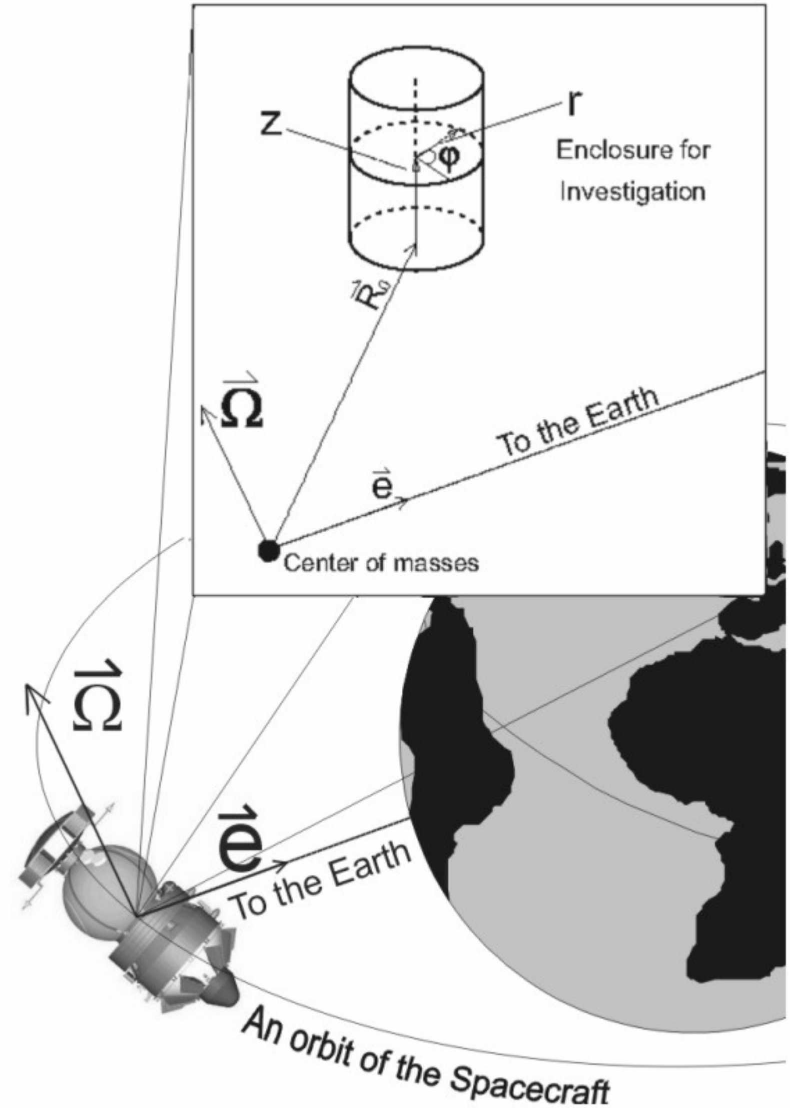
$$\frac{1}{\rho}\nabla p+\beta_t(T-T_0)n+r\times\frac{d\Omega}{dt},$$

$$\nabla u=0,$$

$$\frac{\partial T}{\partial t}+(u\nabla)T=a\Delta T,$$

$$\frac{\partial C}{\partial t}+(u\nabla)C=D\Delta C,$$

$$n=R\times\frac{d\Omega}{dt}+(\Omega\times R)\times\Omega+\Omega_E^2[3(e\cdot R)e-R]+n_a$$



Global benchmark

A. MICROACCELERATIONS

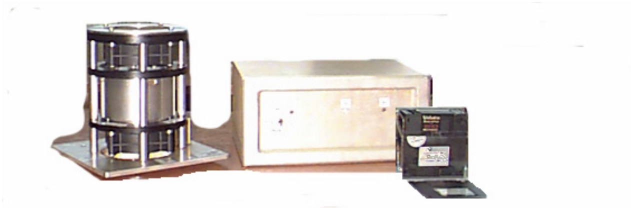
Different teams calculations and comparison
Comparison of the microaccelerations measurements (MAMS, SAMS-II, IMU-128)
Comparisons between theoretical models and measurements of microaccelerations
Preparation of the microaccelerations data in a form available for CFD use

B. MEASUREMENT OF THE THE GRAVITY-DEPENDENT PROCESSES (convection, sedimentation etc.)

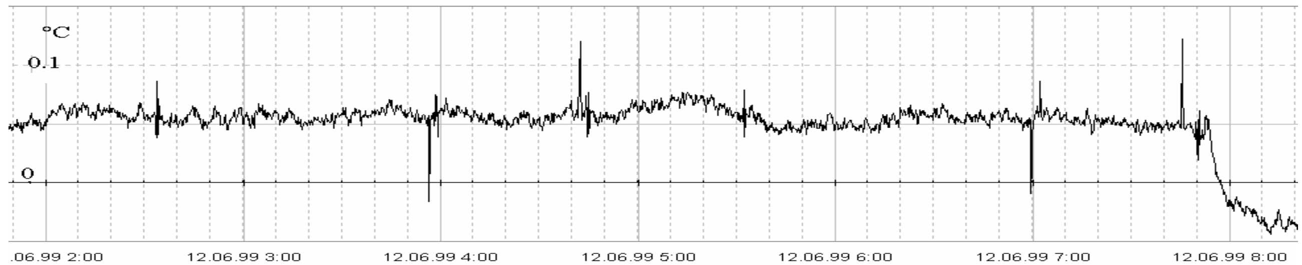
C. CFD MODELING, USING REALISTIC MICROGRAVITY ENVIRONMENT

D. GLOBAL COMPARISON B and C

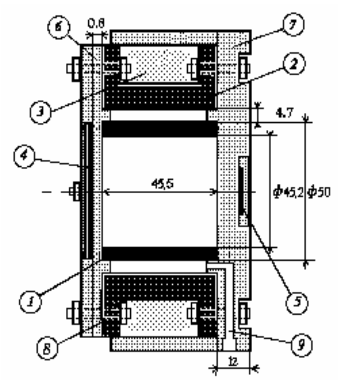
First publication, ground-based experiments and modeling (AIAA 95-0890) Realization on "Mir" : SAMS data, calculations of the QSM, convective sensor DACON, 3D modeling in ground-based and microgravity environment (COSMIC RES. 2001, V. 39, No2)



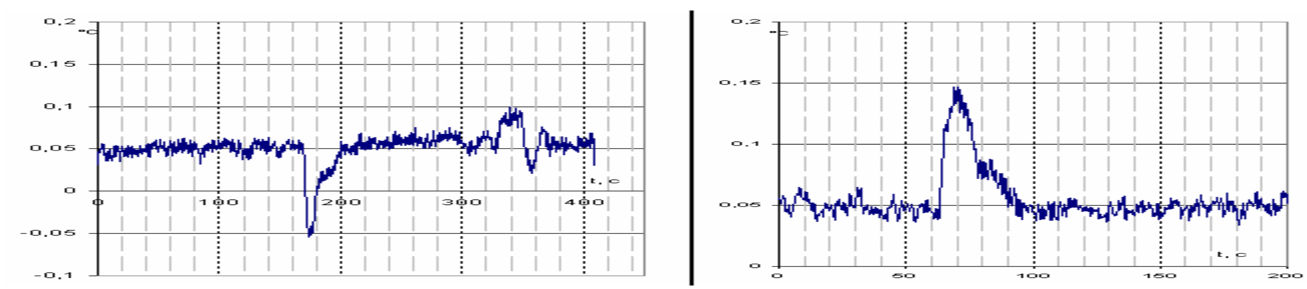
Experimental apparatus “DACON



Temperature signal as a function of time for a 6.5-hour interval during the June 10 – 12, 1999 experiment (location in the module “Kvant” 12 m from the center of mass. The peaks are connected with microaccelerations caused by spacecraft attitude motion and have the maximum values $\pm 1.0 \cdot 10^{-4}$ g_0



Cross-sectional view of test enclosure



MEASUREMENT OF THERMAL CONVECTION AND LOW-FREQUENCY MICROACCELERATIONS ABOARD ORBITAL STATION "MIR"

Putin G.F., Ivanov A.I., Polezhaev V.I. et al. A System for Analysis and Measurement of Convection aboard Space Station: Objectives, Mathematical and Ground-Based Modeling. AIAA 95 - 0890, 33rd Aerospace Sciences Meeting and Exhibit. January 9 – 12, 1995. Reno, NV. 10 p.

Polezhaev V.I., Putin G.F., Ivanov A.I., Sazonov V.V. et al. On the Measurement of Low Frequency Microaccelerations onboard Orbital Station Mir with the Use of Thermal Convection Sensor DACON. AIAA 2000 - 0569, 38rd Aerospace Sciences Meeting and Exhibit. January 10 – 13, 2000. Reno, NV. 12 p.

Tests for Quasi-steady Microaccelerations

O.A. Bessonov and V.I. Polezhaev, Cosmic Research, Vol. 39, No. 2 (2001), 159.

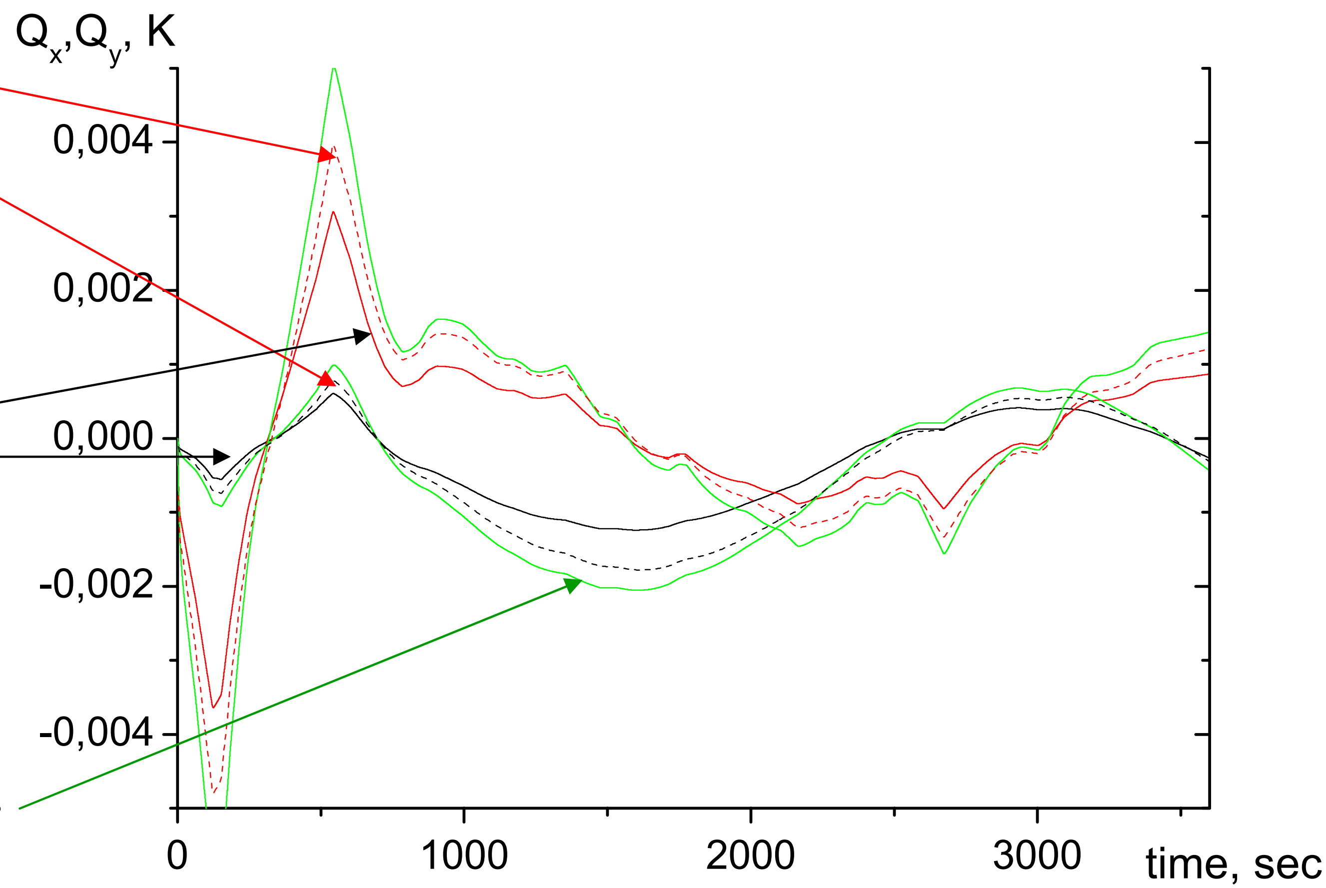
- Conjugate problem
- Finite heat conductivity of cavity wall
- Temperature dependence of physical properties of air

dotted line - results of Bessonov O.A.

Results of test:

solid black and red line - linear profile of the temperature on lateral boundary

green line - adiabatic boundary condition for temperature on lateral wall.



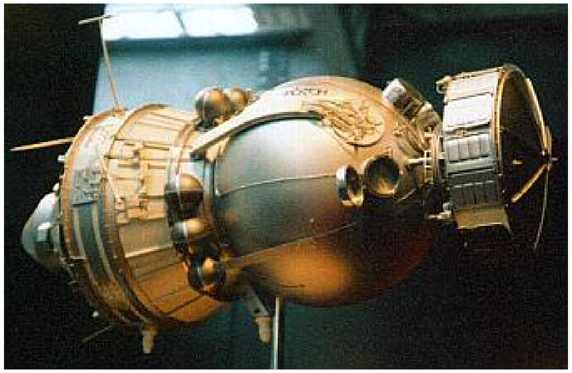
Segregation due to the Convective Heat/ Mass Transfer in Semiconductor Melt

3D simulation of the impurity distribution

Semiconductor melt: $n=0.0013\ cm^2/sec$, $Pr=0.016$, $Sc=10$, $\beta_t=2.5\cdot10^{-4}$

Cylinder by diameter 1 cm and length 4 cm

Realistic microgravity environment of “Photon-11”



V.S. Zemskov, M.R. Raukhman, V.P. Shalimov, Cosmic Research, Vol. 39. No. 4 (2001), 359.

N.V. Nikitin,V.I. Polezhaev and V.P. Yaremchuk, Proceedings of 3th Russian National Conference on Heat Transfer. Vol. 3 (2002), 124 (in Russian).

Numerical Modeling of Convective Heat and Mass Transport in the Semiconductor Melt

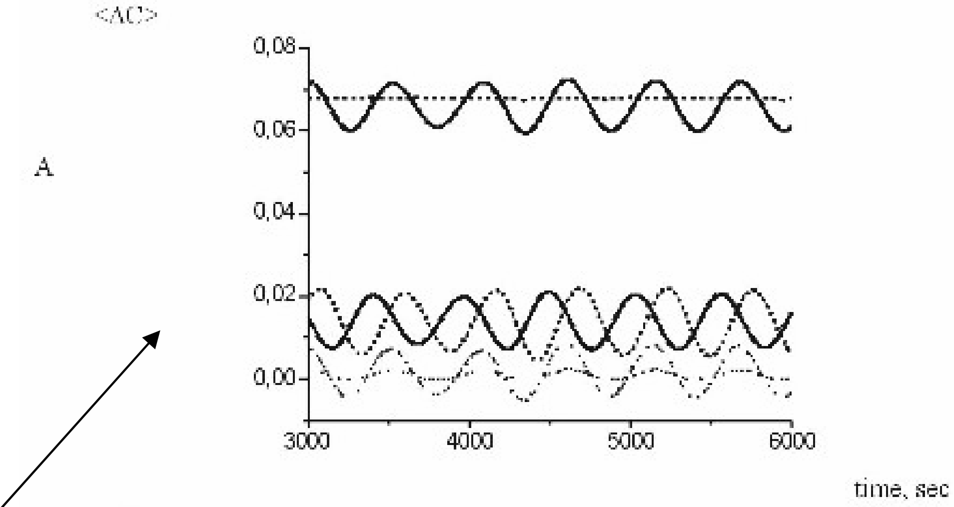
The average concentration stratification defined as follows:

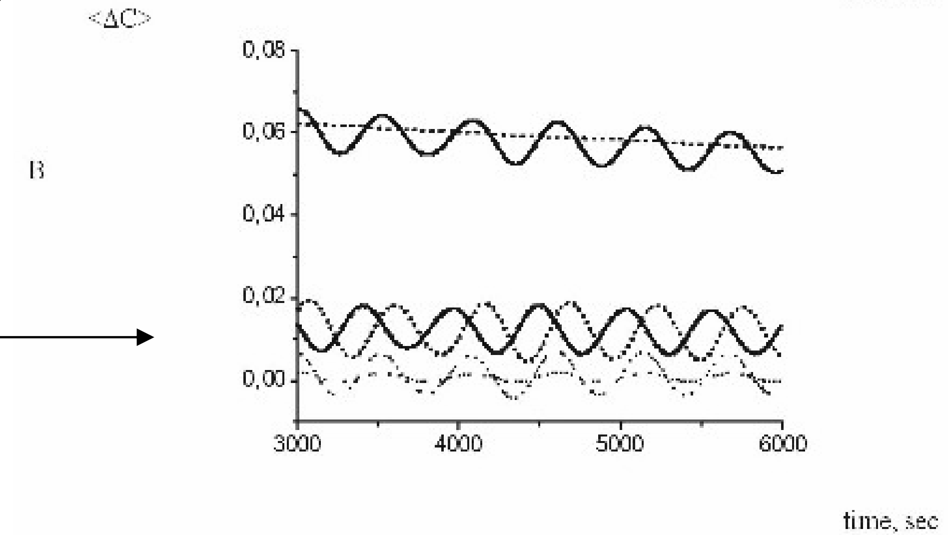
$$< \Delta C >= \frac{1}{H}\int^{H}\left(C(0.5,\varphi,z)-C(0.5,\pi+\varphi,z)\right)dz$$

Average concentration segregation <ΔC> in two cross-sections (*r*; φ=0, 180; *z*) and (*r*; φ=90, 270; *z*) parallel to the cylinder axis.
Solid line – cylinder axis parallel to axis X of vehicle coordinate system, dashed line – Y, dotted line – Z.

A – constant concentration on the crystallization front,

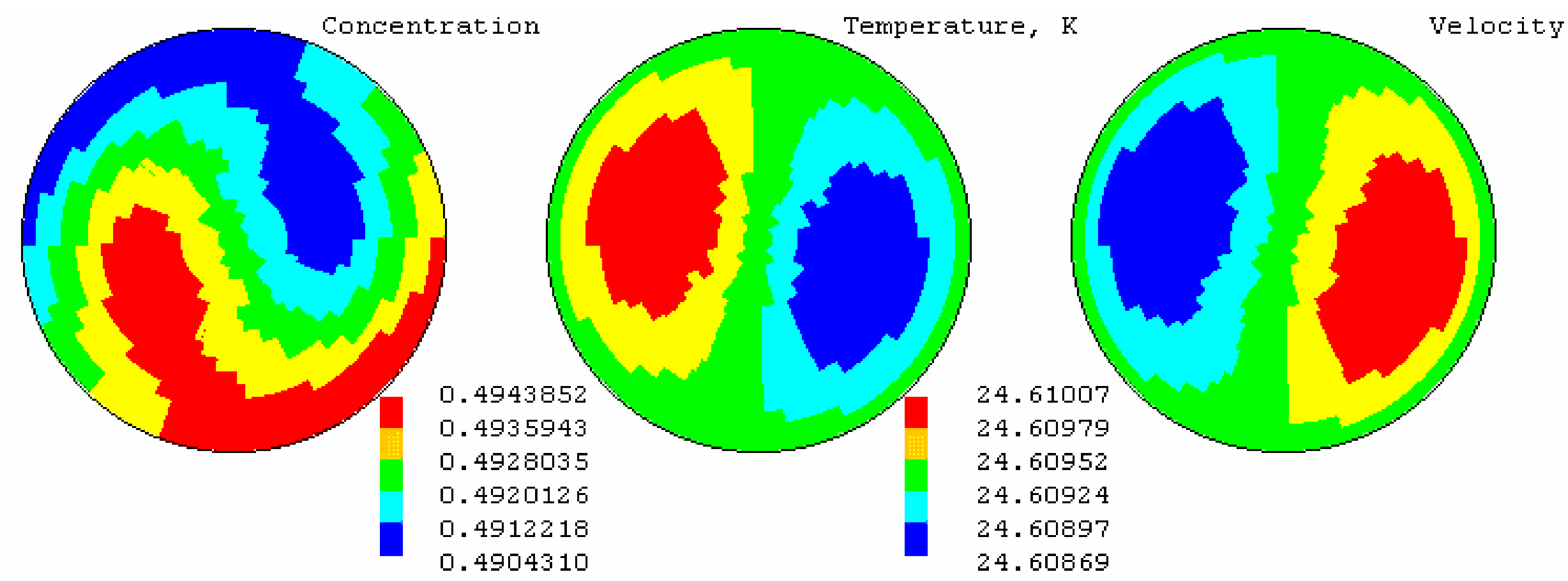
B – mass transfer boundary condition on the crystallization front.





3D Effects of Convective Heat and Mass Transfer in the Semiconductor Melt

- **if the axis of the cylindrical volume is parallel to axis X or Y of the spacecraft coordinate system,**
- **then, the mean values of concentration, temperature and velocity field weakly differ from the instant values,**
- **but for Z orientation, the mean values significantly differ from the instant values**
- **the flow changes its direction due to the change of projection of the microgravity vector on the temperature gradient**

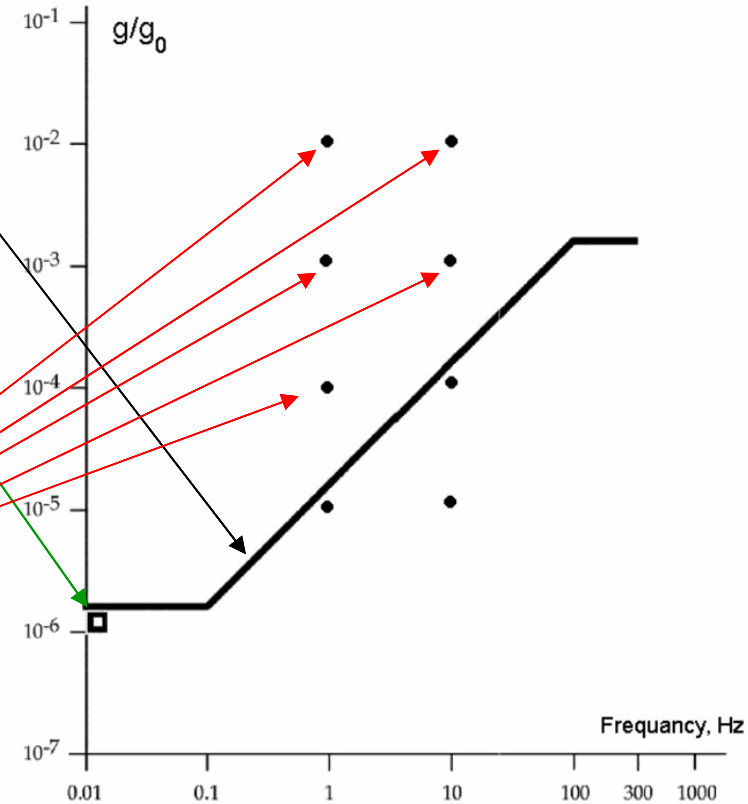


Modeling Results & microgravity limits

- ISS combined requirement accelerations limits

- The main component of the microgravity acceleration of "Photon-11" spacecraft.

- Vibrations without residual accelerations.

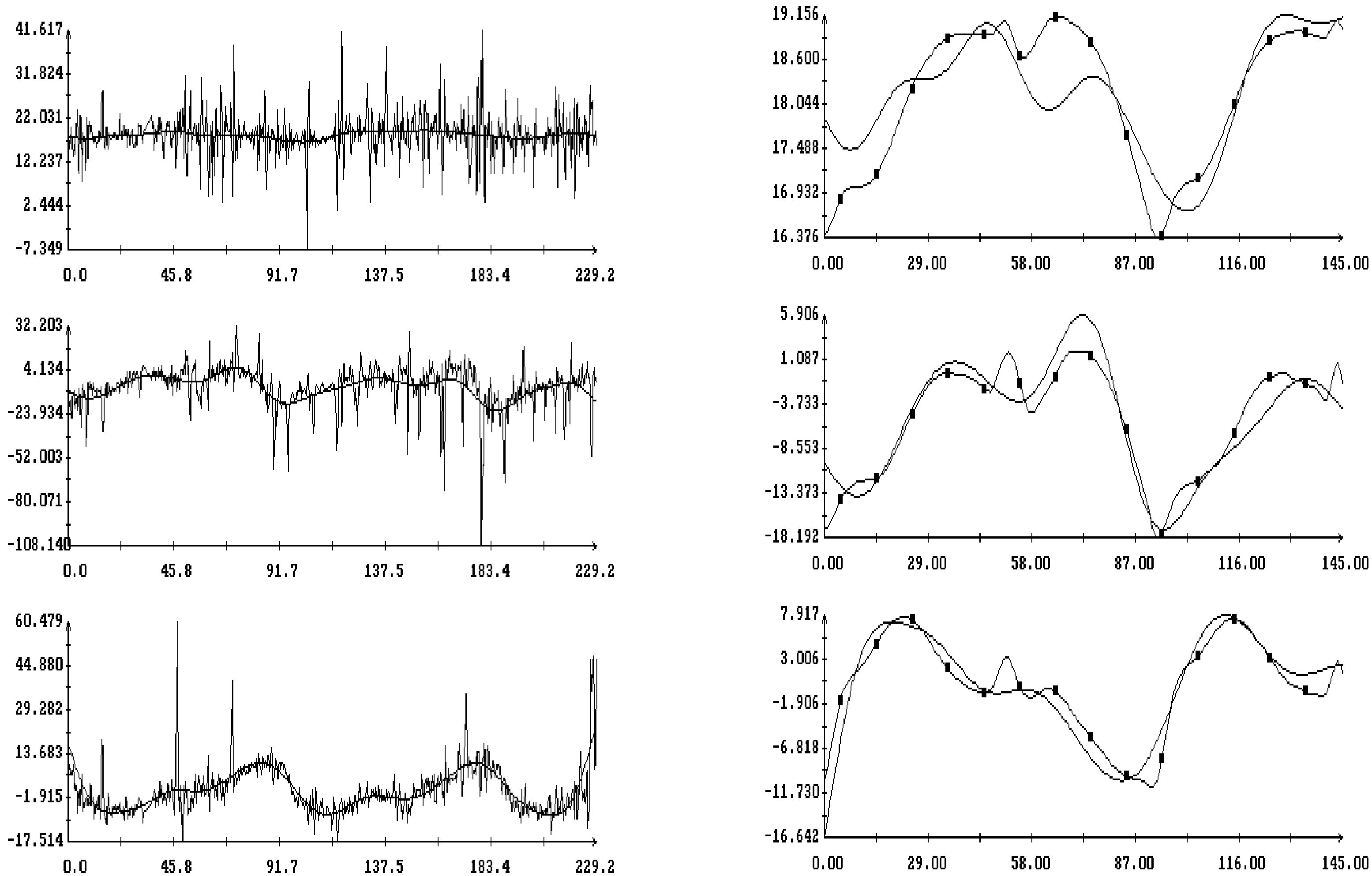


Results of simulation:

- Requirement limits for the quasi-steady acceleration for crystal growth processes must be lower.

- Vibrations do not induce significant concentration segregation if the amplitude does not significantly exceed the acceleration requirement limit

The Use of Microaccelerations Data for Convection Modeling & Analysis of the Microaccelerations Limits



Low frequency microacceleration measured by MAMS on ISS (left) and comparison of the measurements and calculations (right)

MODEL OF CONVECTION FOR GENERAL CASE OF SPATIAL AND TEMPORAL MICROACCELERATIONS

$$\frac{\partial u}{\partial t} + (u\nabla)u + 2(\omega \times u) = \nu \Delta u - \frac{1}{\rho}\nabla p + \beta\left(T - T^{o}\right)n + r \times \dot{\omega}$$

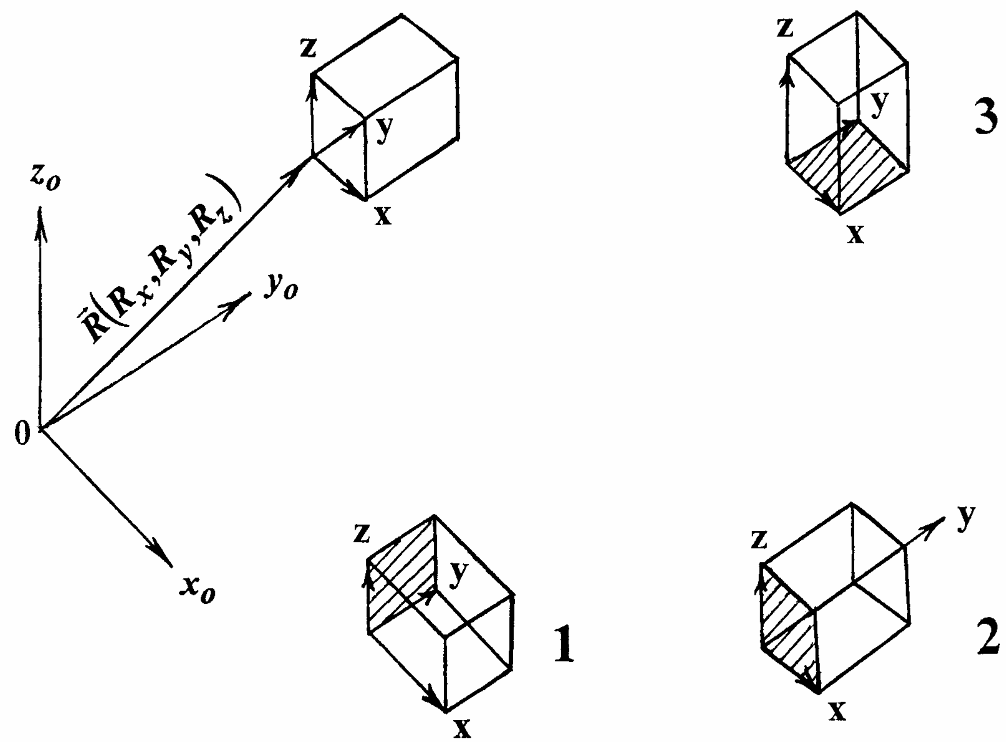
$$\nabla u = 0, \qquad \frac{\partial T}{\partial t} + (u\nabla)T = \alpha \Delta T, \qquad \frac{\partial C}{\partial t} + (u\nabla)C = D\Delta C.$$

Here **u = u(r,t)**- velocity , **T = T(r,t)** и **p = p(r,t) -** temperature and pressure, ν**,** α**, D** and β - viscosity, thermal diffusion, diffusion and thermal expansion coefficient.

Vectors **n** и ω - time dependent functions for the general case of space flight. All parts of the microaccelerations **n** may be include in the pressure, besides first, using angular velocity and buoyancy type part n_0, which includes linear motion and rotation.

SPECIALIZED SYSTEMS COMGA_S & COMGA _W, CONVECTIVE HEAT/MASS TRANSFER PROCESSES

DOS / WINDOWS versions of the "COMGA" system for realistic space flight



3D case approximates using 2D cases

$$g_x(t) = g_{xo} + [g_s + g_t * \sin(\Omega_1 t)] * \sin(\Omega_2 t + \varphi_o)$$

$$g_y(t) = g_{yo} + [g_s + g_t * \sin(\Omega_1 t)] * \cos(\Omega_2 t + \varphi_o)$$

g_{xo} and g_{yo} are components of the constant microacceleration; g_s and g_t are constant and variable components, respectively, due to rotation if they exist; Ω_1 and Ω_2 are frequencies of vibration and rotation; φ_o is initial angle of inclination.

General case of the orbital flight with angular acceleration

n/go = f (x,y,z,t) ,

includes a number of elementary motions:

-gravity-driven convection for the constant and gravity gradient field, central-symmetrical field),

- convection, induced by :

- rotation,

-vibration,

-motion with angular acceleration etc.

Calculation of the microaccelerations in a form suitable for fluid mechanics computer systems and analysis of gravitational sensitivity

PLAN FOR SESSION I

Definitions and common version of computer laboratory

1. Microacceleration's regimes, elements of gravitational sensitivity, general characteristics of fluid flow and heat/mass transfer

2. Definition of the system, numerical schemes parameters, classifications and contents of computer laboratory

3. Definition of modeling, criteria of convection, heat/mass transfer (Rayleigh, Marangoni, Prandtl, Schmidt numbers etc.

4. Definition and contents of the computer laboratory and the operating system

5. Demonstration of the elementary examples of the convection in zero and low gravity regimes using the system and computer laboratory

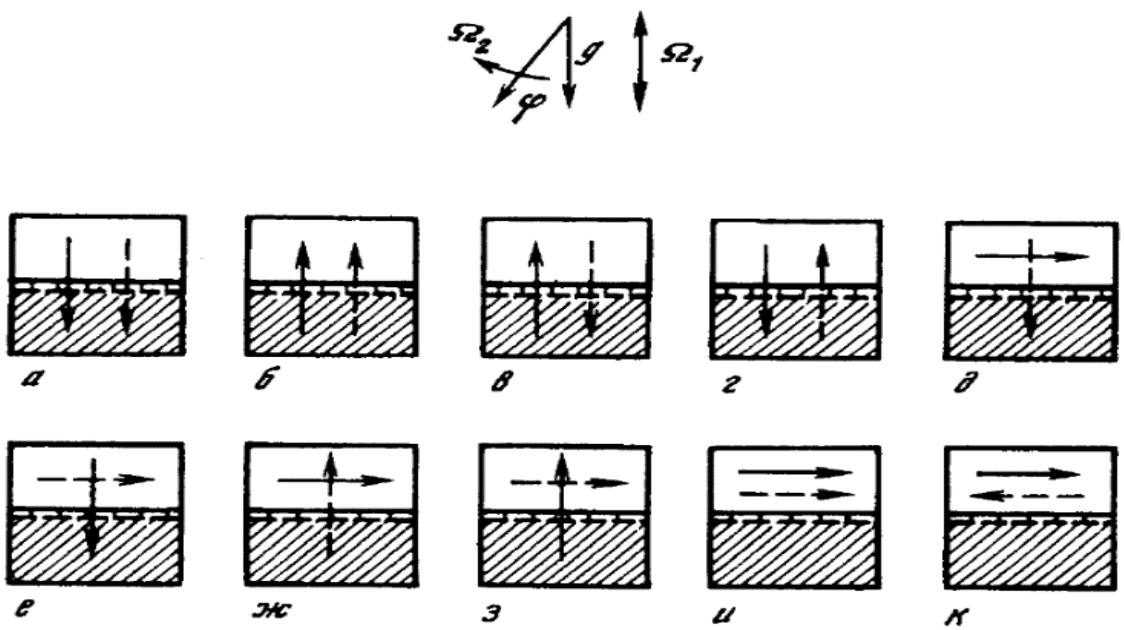
COMMON COMPUTER SYSTEM "COMGA"

(COnvection in MicroGravity and Applications)

Classification for the problems of convection in an enclosure with rigid (solid line) or free boundaries (dashed line) in the field of gravity (g), vibration (Ω_1) and rotation (Ω_2) for binary mixture

Covers cases : zero gravity (n=0), low gravity (g/go<<1) and effective low gravity regimes

Arrow- direction of the heat flux, dashed arrow - direction of the mass flux

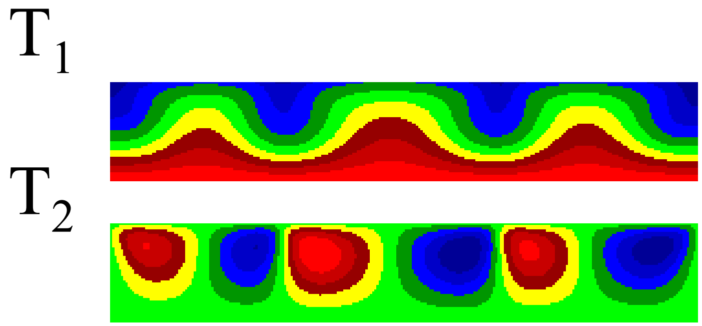


Zero gravity regime (n=0)

Thermocapillary Marangoni convection

$Ma = \sigma_T \Delta T H / \rho \nu a$

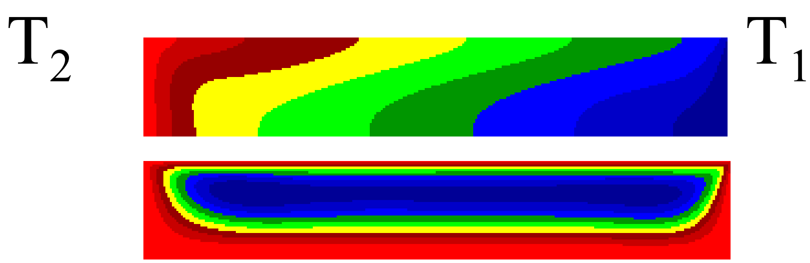
$Pr = \nu / a$



Isotherms

Stream function

Marangoni instability (bottom heating), $T_2 > T_1$

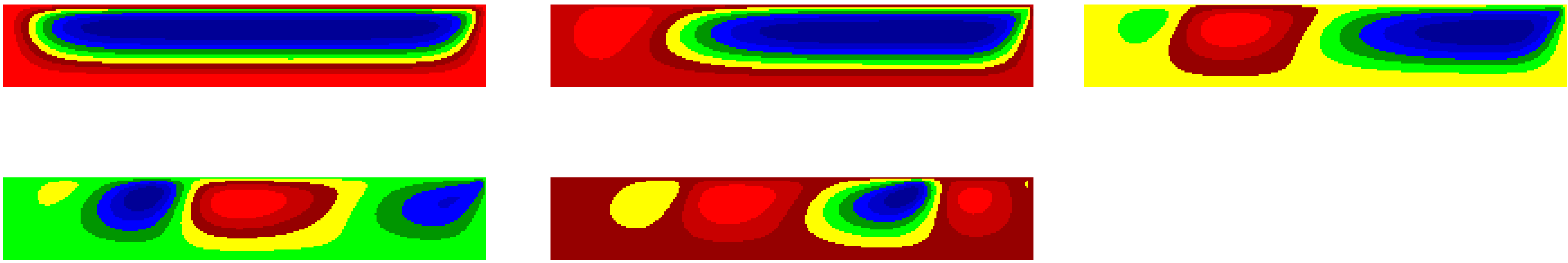


Layer with side heating, $T_2 > T_1$

$Ma = 1000$, $Pr = 1$, $H/L = 6$

Zero gravity regime

Thermosolutal (double diffusive) Marangoni convection $Ma=\sigma_T \Delta TH/\rho\nu a$, $Ma_c= - \sigma_C \Delta CH/\rho\nu D$, $Sc=\nu/D$



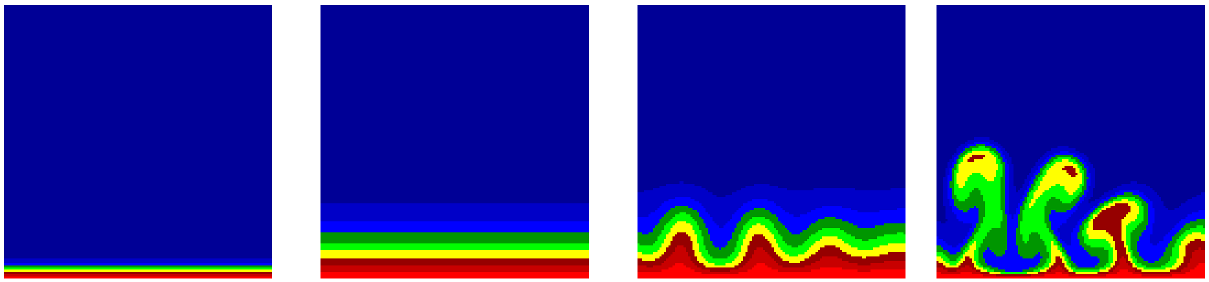
$Ma=100$, $Ma_c=1.110^3$ $Pr=0.1$, $Sc=10$, $L/H=6$

Oscillations of the flow, temperature/concentration fields in zero gravity induced by coupling between surface tension (temperature /concrentration) gradients

Low gravity regime

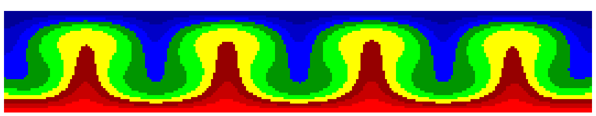
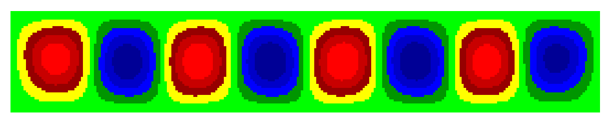
Thermal gravity-driven convection

$Ra = g\beta_T \Delta T H^3/\nu a$



Isotherms

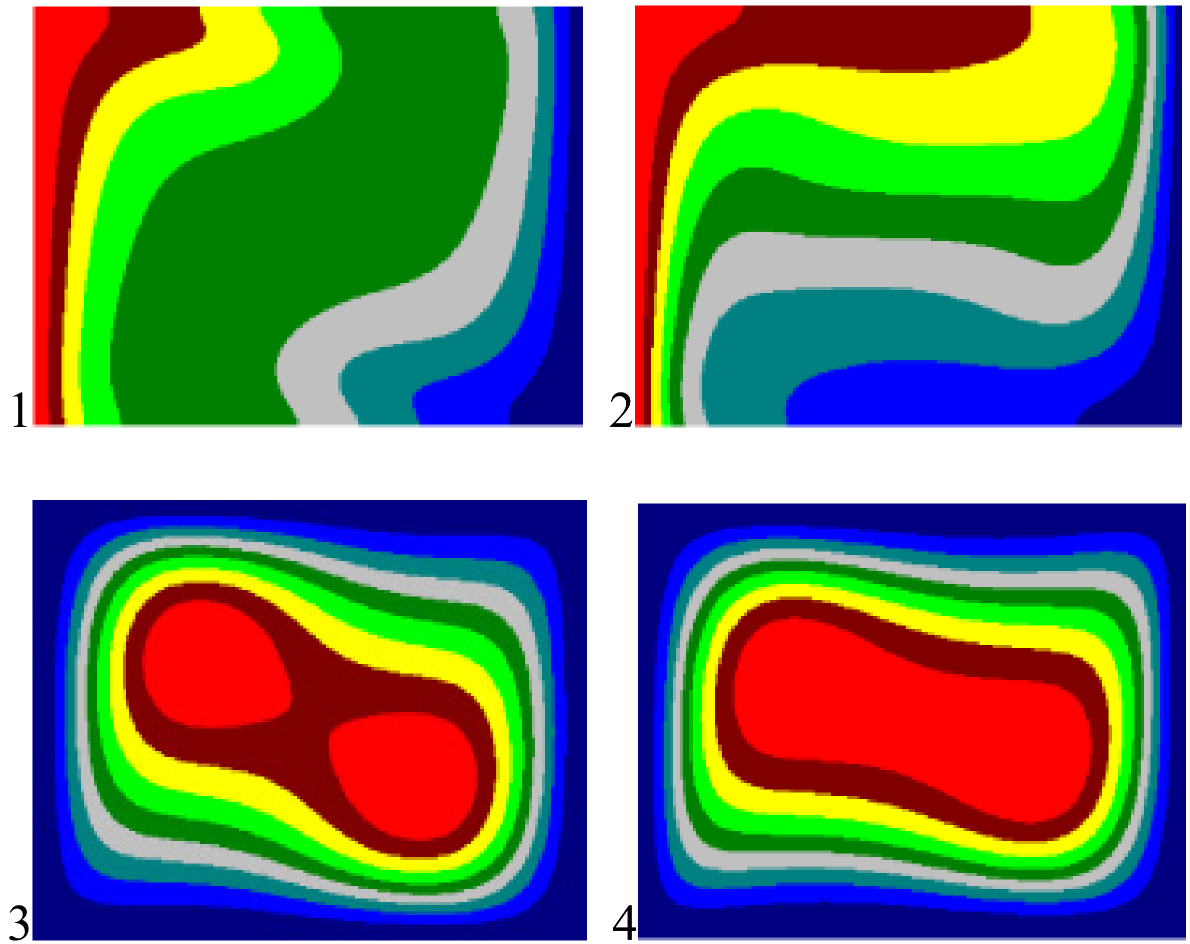
Evolution of (Rayleigh-Benard) instability (thermals) for bottom heating, $Ra = 310^{6}$, $Pr = 0.71$, $L/H = 1$

a  b 

**Steady state regime for bottom heating ($Ra = 10^4$, $Pr = 1$, $L/H = 6$)
a) temperature field, b) flow field (roll structures)**

Thermal gravity-driven convection (side heating)

Ra= 10^5, Pr =1, L/H=1



1-2 - temperature fields; 3-4 - stream function

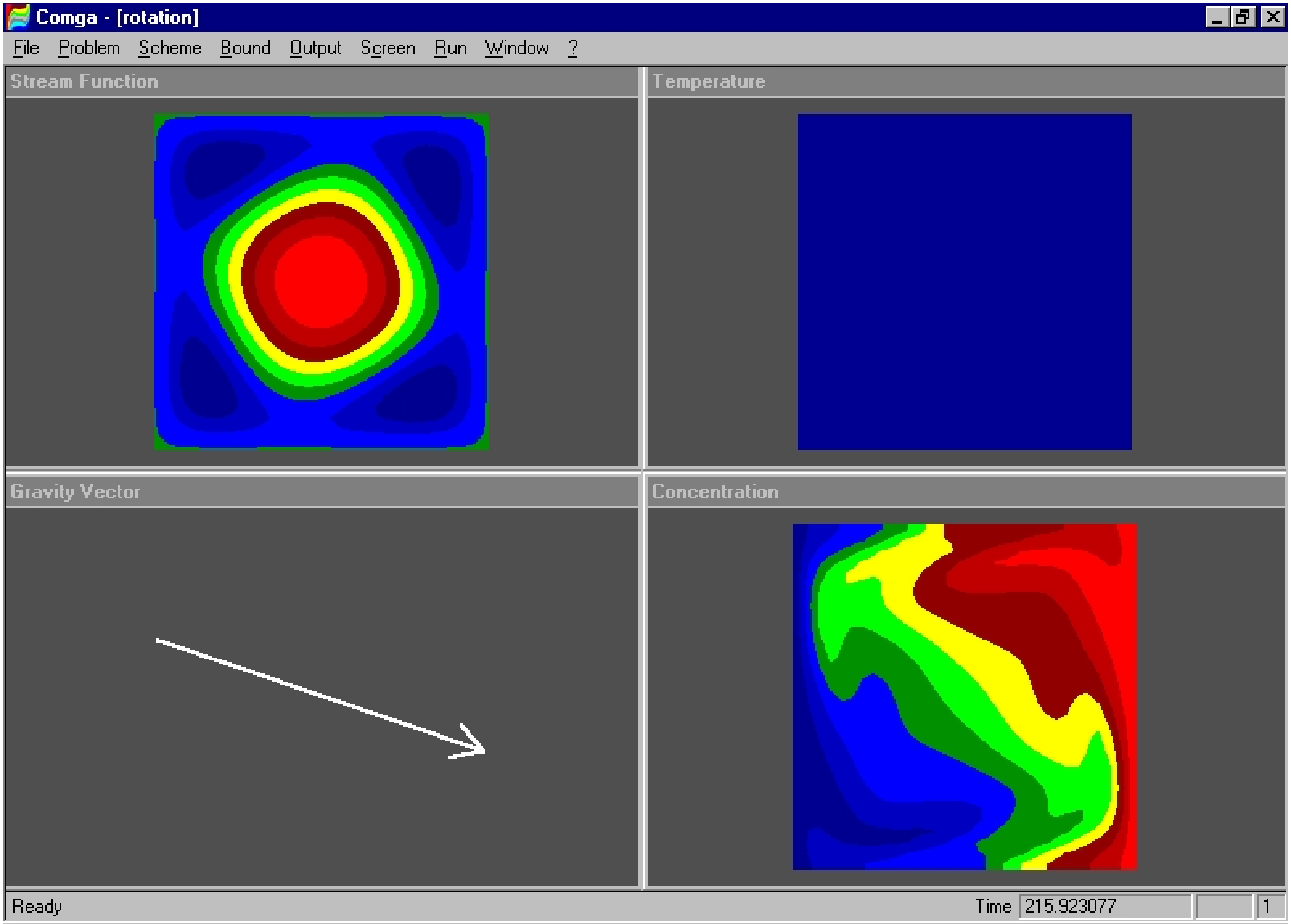
PLAN FOR SESSION II

Elements of the microgravity environment

(parametrical study)

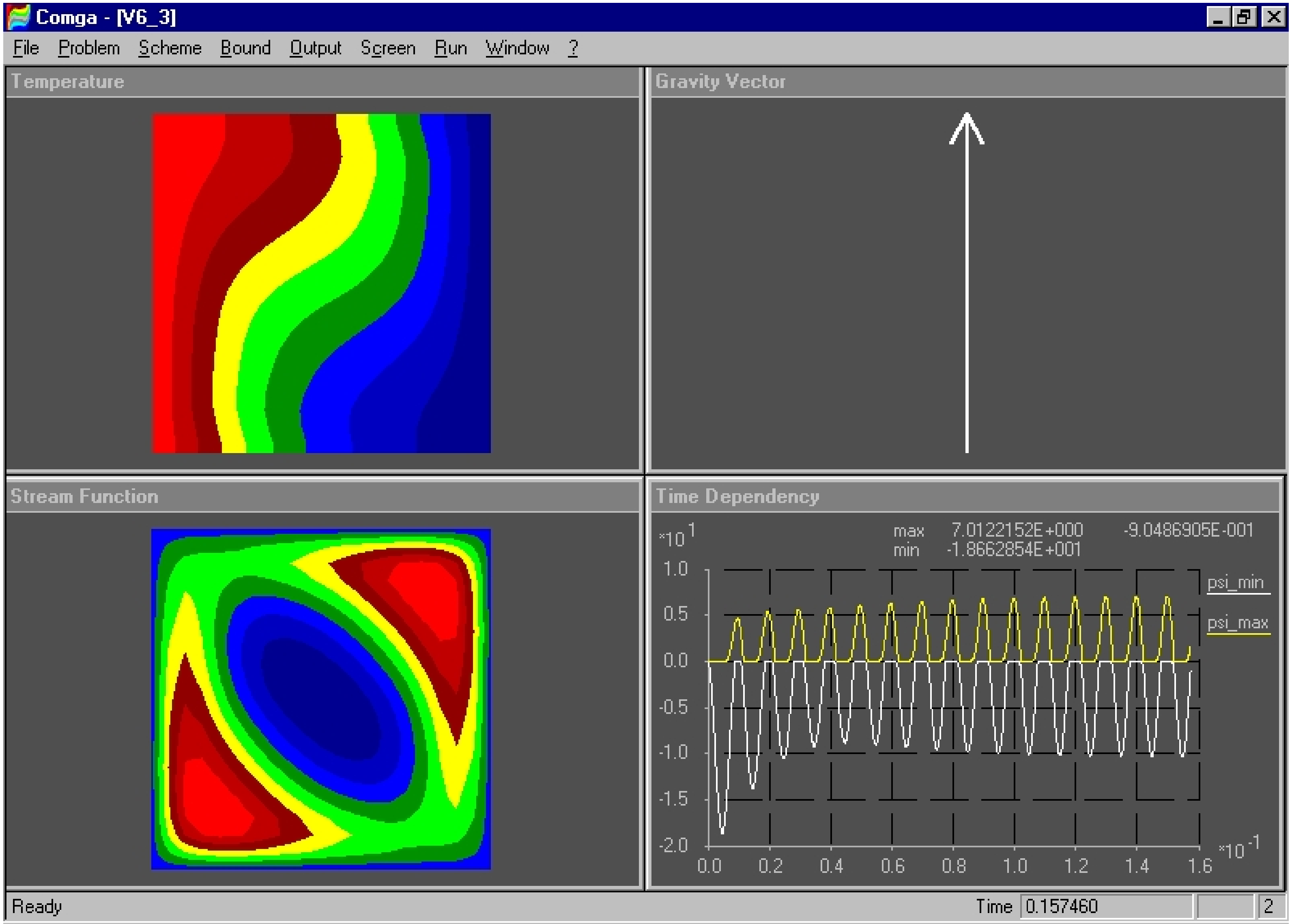
1. Definition of the parametrical analysis using microacceleration, n
2. Direct impact of the angular acceleration (nontranslatory vibration) ("isothermal convection")
3. Translatory vibration impact:
- vibrational vector is perpendicular to the gradient of heat flux
- vibrational vector is parallel to the gradient of heat flux (convective instability)
4. Rotation of the microacceleration vector
5. Other elements of the microaccelerations (gravity gradient, centrifugal acceleration etc.)
6. Diagram for the coupling of the different actions

«ISOTHERMAL CONVECTION»(angular acceleration)



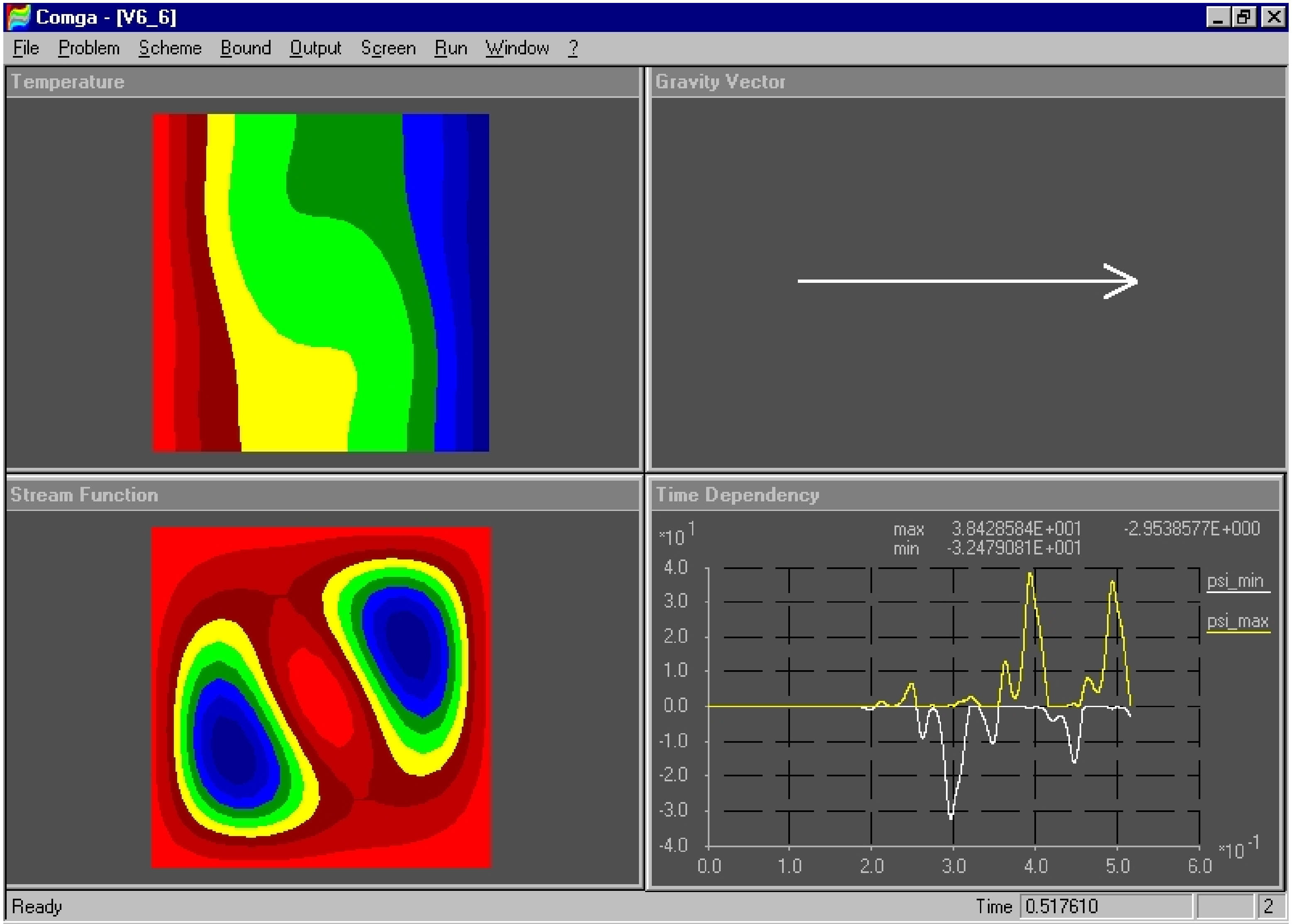
$\omega L^2/\nu=300$, $(d\omega/dt)L^4/\nu^2=10^5$, Pr =0.01, Sc=10, L/H=1

VIBRATION (perpendicular to the temperature gradient)



$$Ra_A = 10^5,\ f\cdot L^2/\nu=100,\ Pr=1,\ L/H=1\ (Ra_v=1.25\cdot 10^6)$$

VIBRATION (parallel to the temperature gradient)

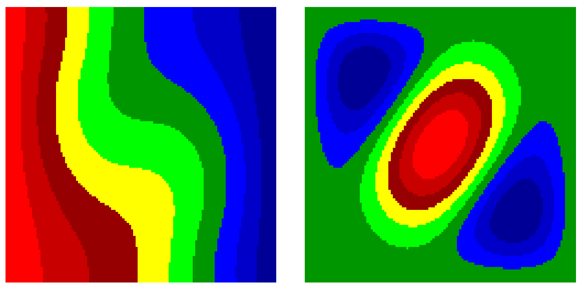


$Ra_A = 10^5$, $f \times L^2/\nu = 20$, $Pr = 1$, $L/H = 1$ ($Ra_v = 3 \times 10^5$)

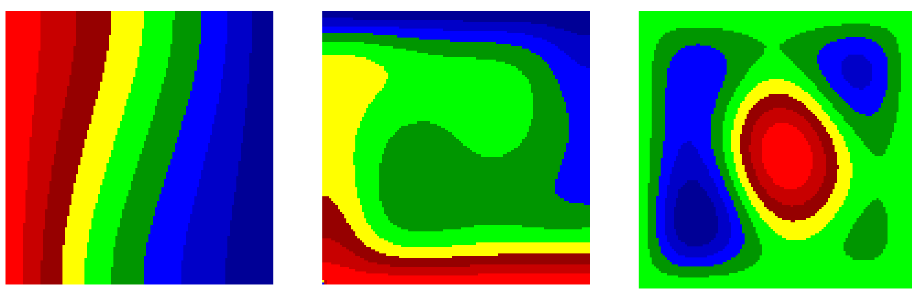
Rotation of the microacceleration vector

a) temperature and flow fields

Ra= 10^4, $\omega L^2/\nu$=1
Pr =1



b) tempeture, concentration and flow fields



Ra= 10^4, $\omega L^2/\nu$=1
Pr =1, Sc=10, Ra_c= 10

PLAN FOR SESSION III

Specialized computer laboratory using realistic microgravity environment

1. **Definition of the realistic microgravity environment quasi-steady microacceleration and format of the data for the computer code "Vectors"**
2. **Analysis of the terms in the microacceleration, n, for a given spacecraft / payload positions**
3. **Menu and operation of the system COMGA.**
4. **Example of modeling using calculations of the quasi-steady accelerations**
5. **The use of the measurement data of the low frequency accelerations**

Preparing the Microacceleration, n, data for the COMGA code

File : d051101.bnd duration = 4590 sec (FGB center of mass)

position relative to ISS center of mass: rx=1046.1cм, ry=33.2cm, rz=39.3cм

x-component (microG = 1e-3 cm/s/s):

	mean	min	max
total acceleration, nx	-1.442	-1.479	-1.345
gravity gradient	-1.298	-1.347	-1.157
aerodynamic drag	-0.157	0.243	-0.105
angular acceleration	0.001	0.021	0.021
centrifugal acceler.	0.013	0.007	0.023

y-component (microG = 1e-3 cm/s/s):

	mean	min	max
total acceleration, ny	0.191	-0.334	1.193
gravity gradient	0.197	-0.117	0.858
Aerodynamic drag	-0.014	-0.038	0.012
angular acceleration	0.009	-0.391	0.322
centrifugal acceler.	-0.000	-0.016	0.010

z-component (microG = 1e-3 cm/s/s):

	mean	min	max
total acceleration, nz	-0.235	- 0.669	0.313
gravity gradient	-0.083	- 0.470	0.399
Aerodynamic drag	-0.129	- 0.198	-0.080
angular acceleration	-0.024	-0.239	0.302
centrifugal acceler.	0.001	-0.005	0.008

angular velocity (*1e-3 1/s):

	mean	min	max
magnitude	0.1195	0.0810	0.1762
x-component	0.0023	-0.1242	0.1010
y-component	0.0016	-0.1438	0.1268
z-component	-0.0248	-0.1225	0.1048

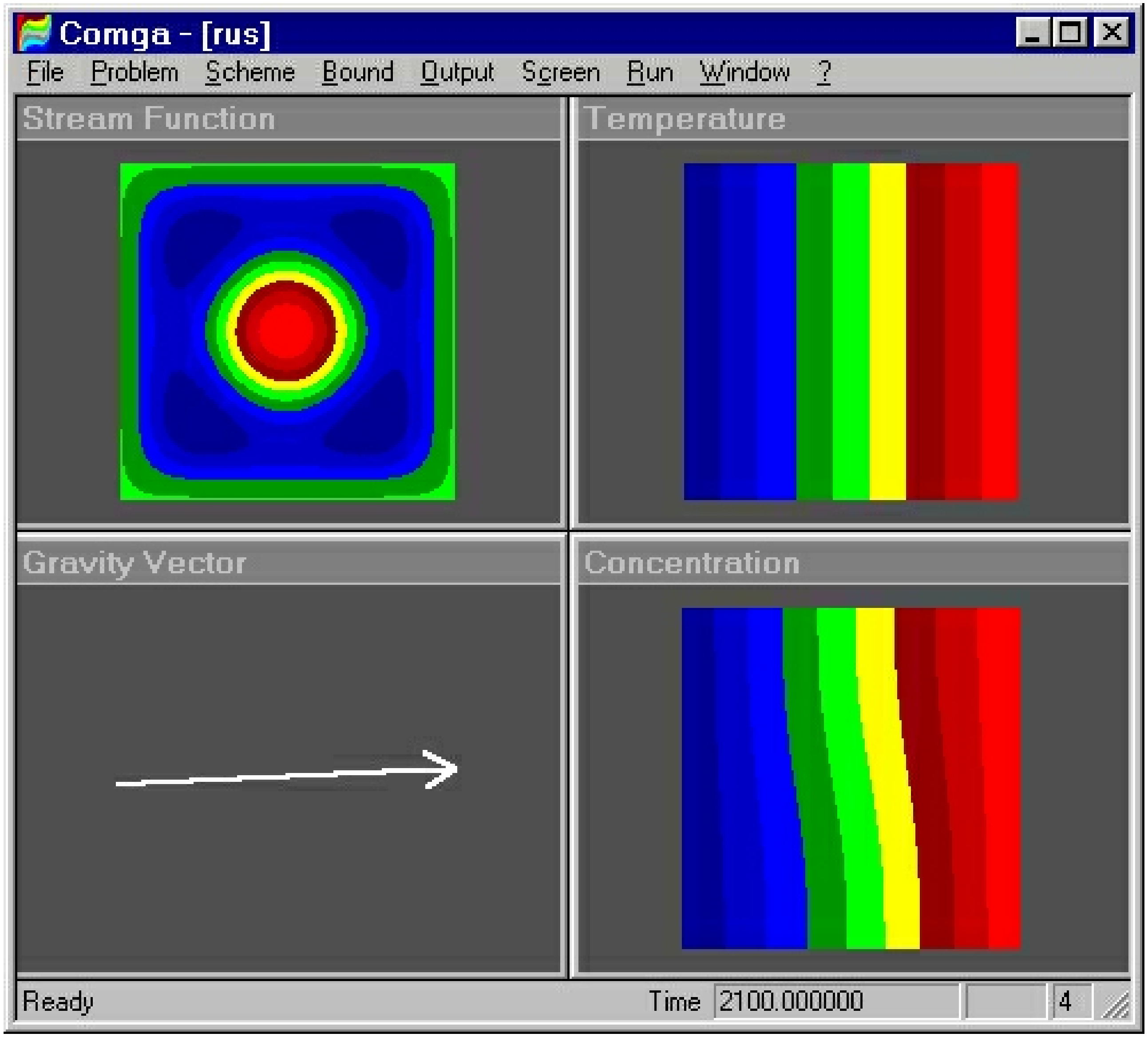
angular acceleration (*1e-6 1/s/s):

	mean	min	max
magnitude	0.2648	0.0005	0.8331
x-component	0.0039	-0.7840	0.6885
y-component	-0.0226	-0.2356	0.2778
z-component	-0.0084	-0.3038	0.3757

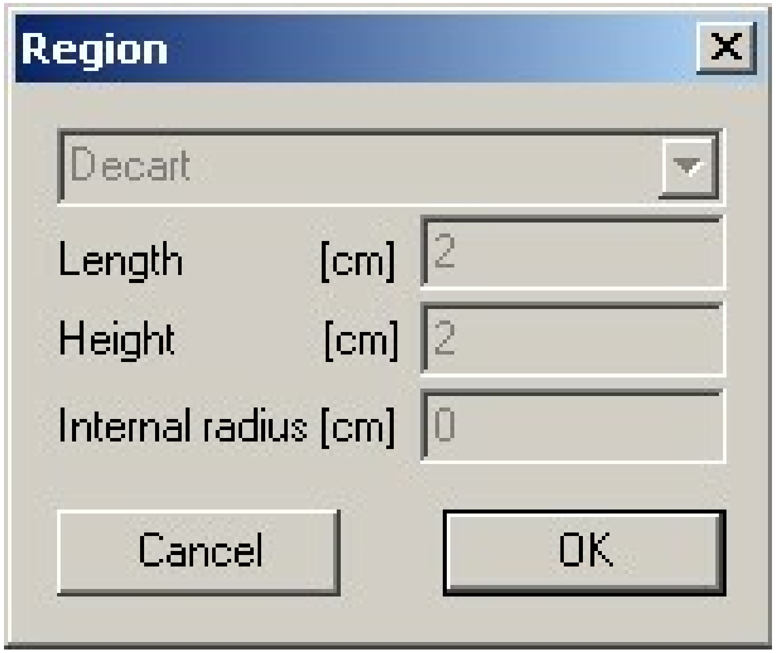
vector magnitude (microG = 1e-3 cm/s/s):

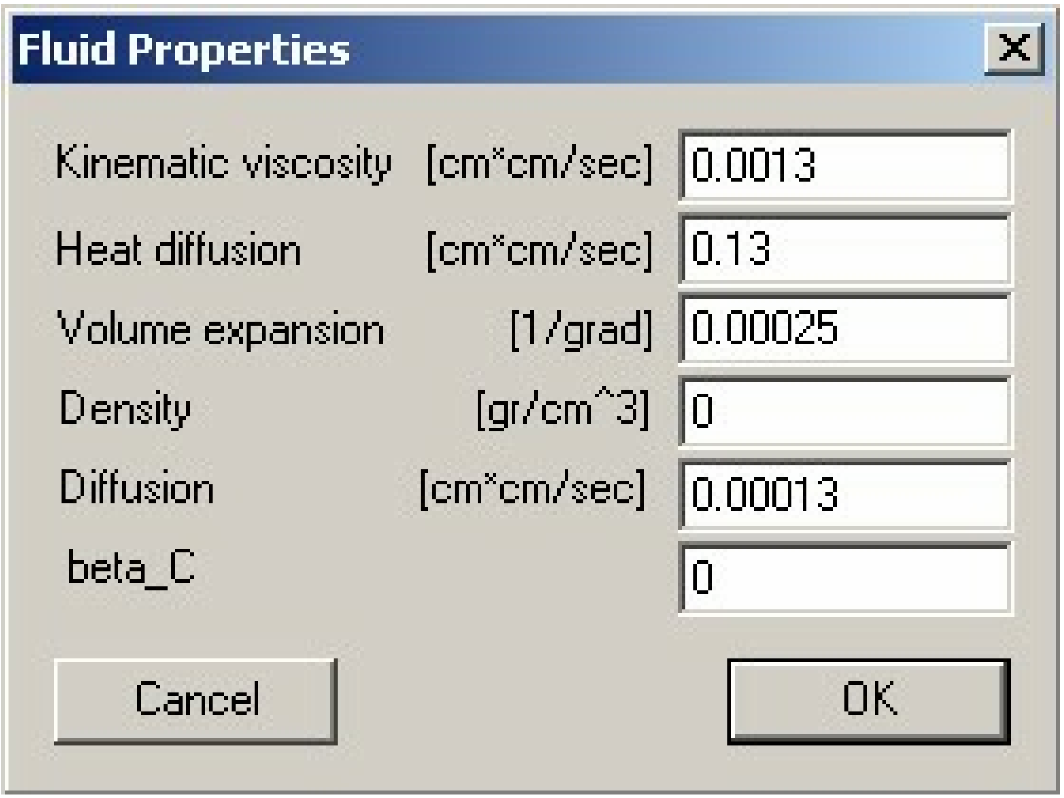
	mean	min	max
total acceleration n	1.550	1.437	1.831
gravity gradient	1.368	1.342	1.443
aerodynamic drag	0.205	0.145	0.313
angular acceleration	0.162	0.000	0.458
centrifugal accelerat.	0.014	0.007	0.025

A system using realistic microaccelerations in space flight



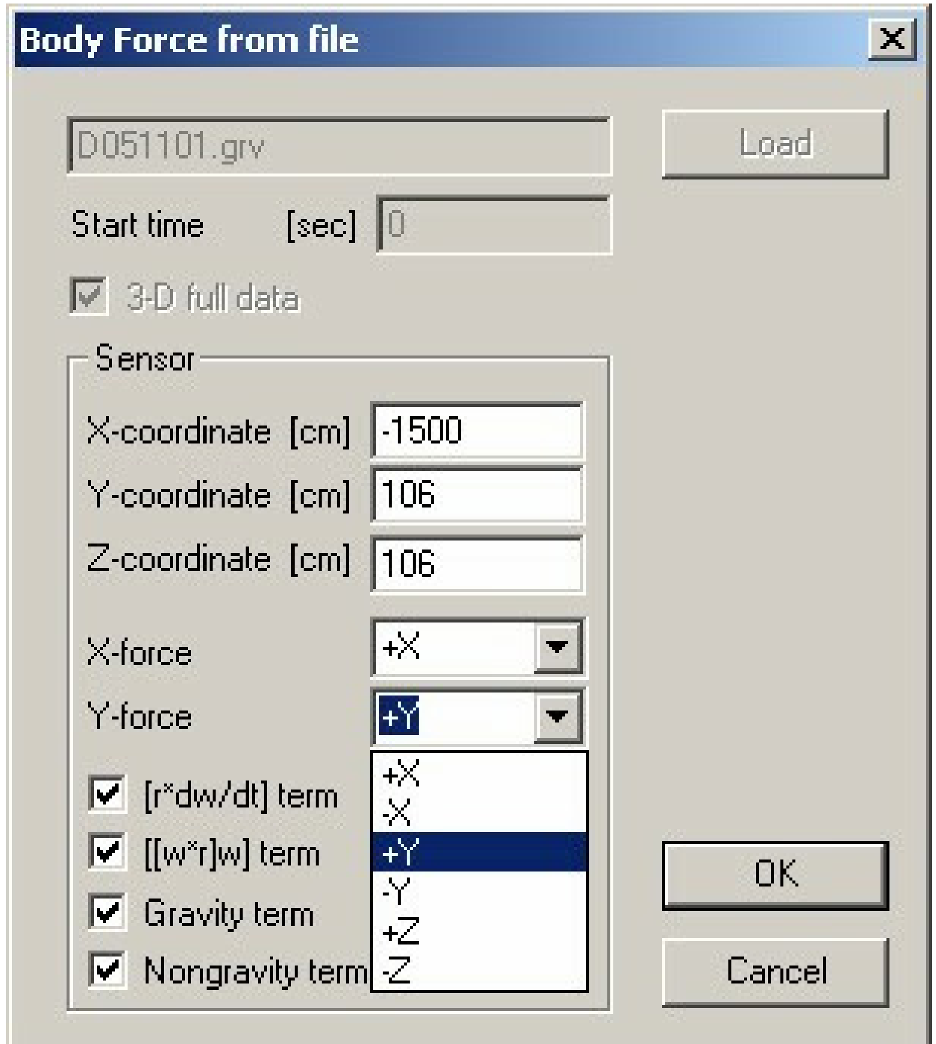
Geometry and properties of the semiconductor melt



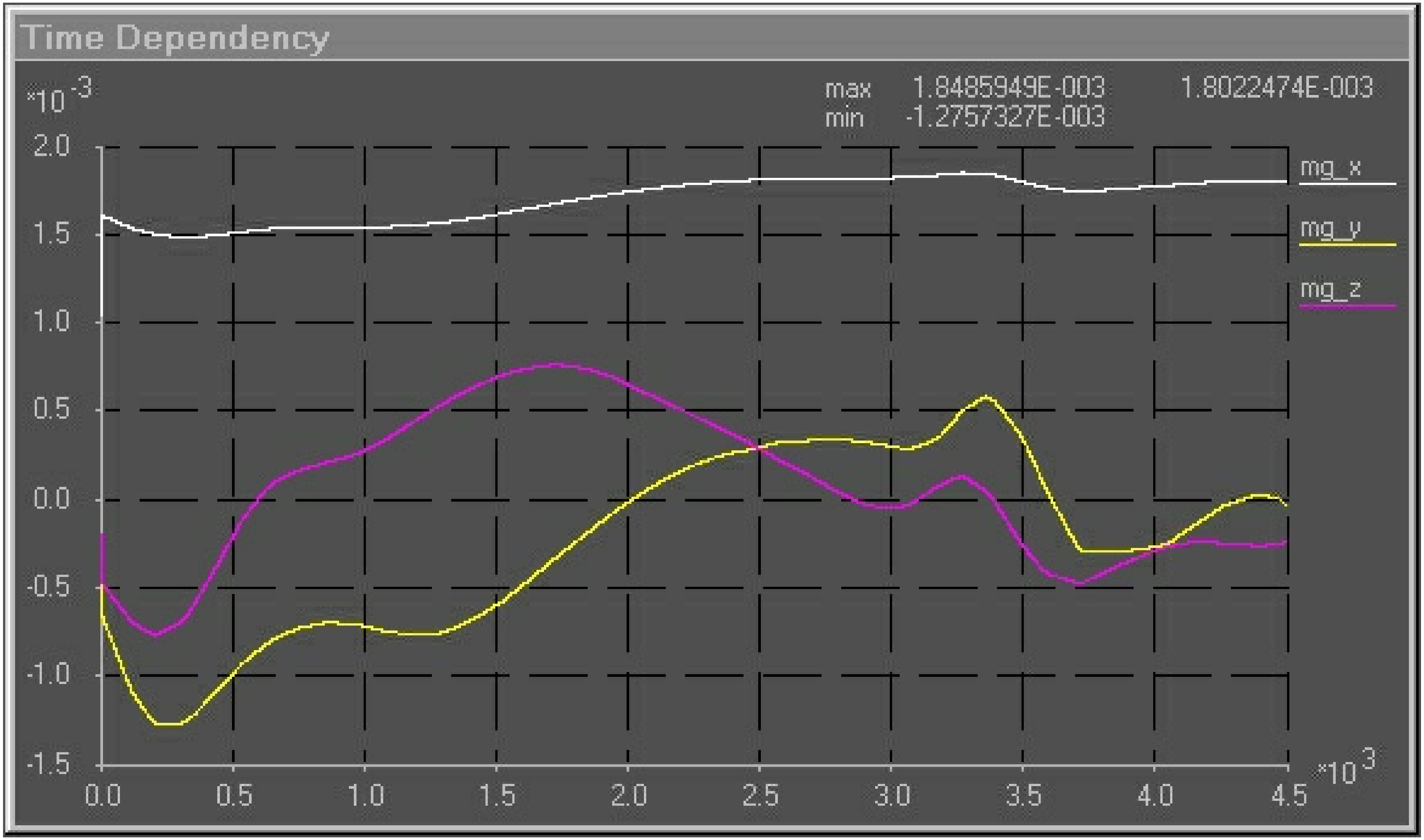


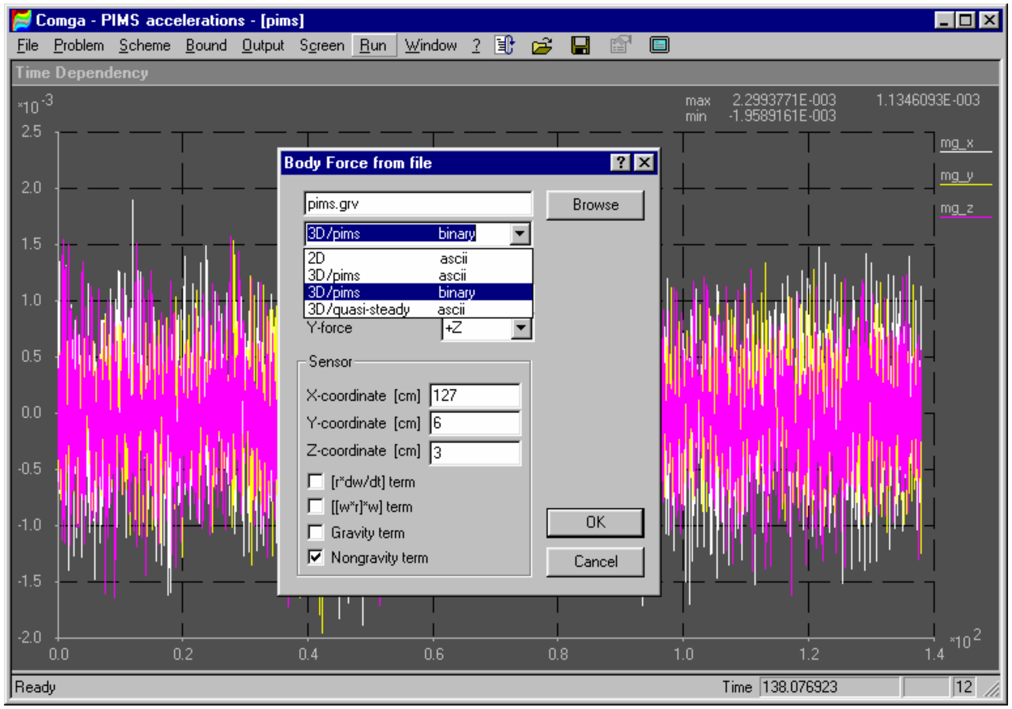
The use of the calculated quasi-steady microaccelerations for RS ISS

Point: X=-1500cm, Y=106cm, Z=106cm



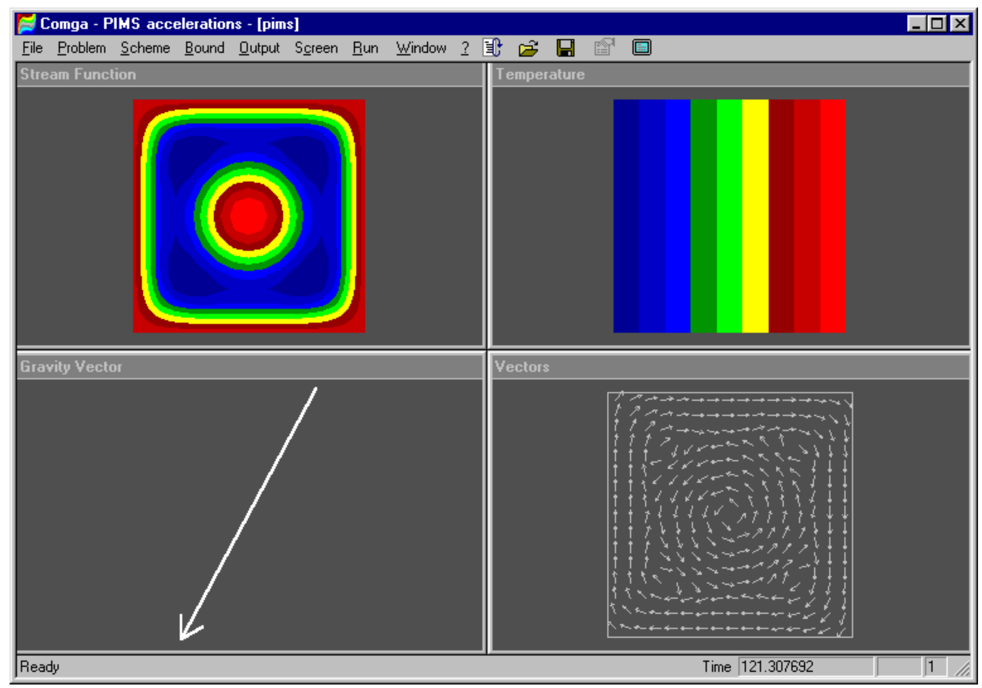
Temporal evolution of the microacceleration components





Measurements data & microacceleration's menu

Flow patterns, isotherms & microacceleration's vector



On-line modeling of the convection on ISS using COMGA with measurements microacceleration by SAMS II

Conclusions

- New project on ISS with the high gravitationally sensitive systems (CRIT)

- A statement of the problem & numerical code for three dimensional simulation of convection & in cylinder under realistic space flight

- Global benchmark project with the use of modification of the DACON on ISS

- Foton spacecraft: 3D modeling of the lateral segregation

- Computer systems with microacceleration interface: tutorial of the use of the calculated(and measured) microacceleration in a realistic microgravity environment

- Express analysis & on-line control of the gravitational sensitivity systems onboard the ISS

Acknowledgments

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