INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

SMR/382- 35

WORKSHOP ON SPACE PHYSICS:
"Materials in Micorgravity"
27 February - 17 March 1989

"Physical Phenomena Important for Life Science Studies Under Weightlessness"

A. JOHNSSON
Department of Physics
University of Trondheim
Dragvoll, Norway

I. General overview of physical phenomena which are, or can be, of importance in Life Science experiments in Space.

II. Sedimentation and its importance in balance systems.
Some fundamental problems as to
a. sensitivity of the balance system (and to a certain extent other systems).
b. a simple systems analysis of a balance system.

III. A Space experiment to study the fundamental properties of mass perception in plants. A case study from the preparation for the IML-1 flight.

IV. Oscillative systems and some aspects on their behaviour in weightlessness:
a. helical plant movements (circumnutations) with a period of 2 h.
b. daily rhythms, with a period of the order of 24 h. The importance of coupling between cells.

V. Some other relevant areas of investigations at the interface between physics and biology.
Some concluding remarks on biology in weightlessness and biophysics.

Anders Johnsson
Dept of Physics /AVH
University of Trondheim
N-7055 Dragvoll
Norway

Telefax: 47-7-920550
Telephone: 47-7-920411

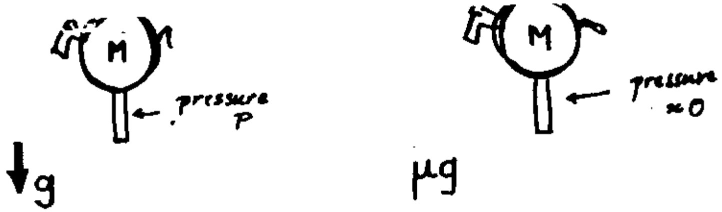
Physical phenomena important for Life Science studies under weightlessness.

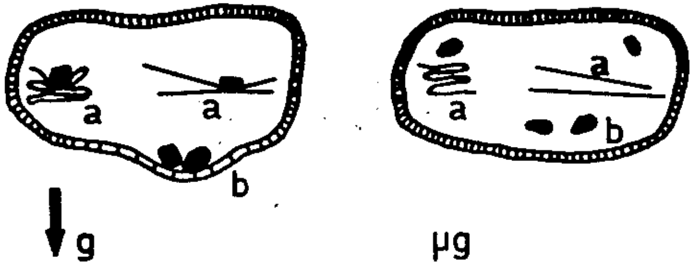
1. Decreased pressure/strain in organisms and cells

→ form of organisms, gravimorphism
→ skeleton, cellulose structures, cytoskeleton etc
→ transport of water, blood etc.
→ strain effects on membranes ⇒ physiological signals?

2. Sedimentation of particles, buoyancy of bubbles etc

→ perception of force vectors (balance systems) in man, animals, plants
→ stirring & mixing effects
→ density gradients ⇒ mixing
→ heat gradients ⇒ convection





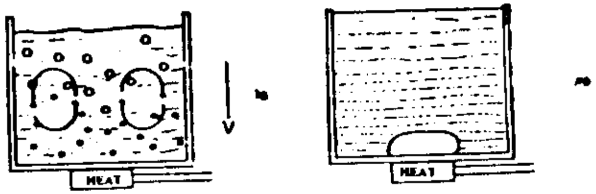
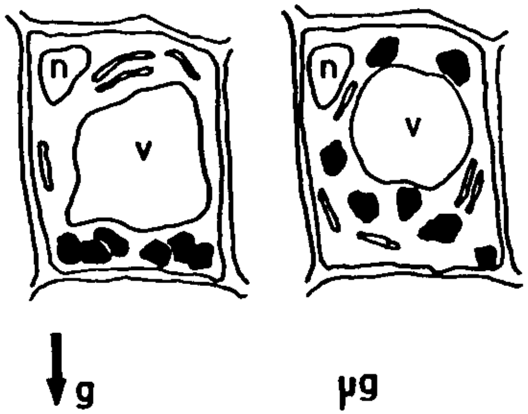
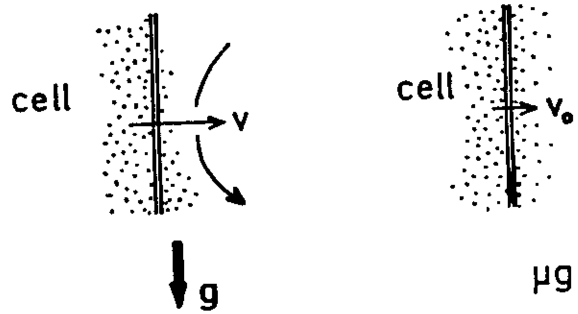


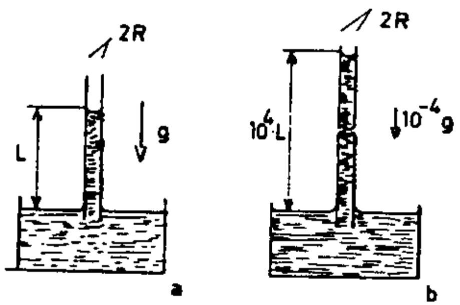
Fig. 1. The left part of the figure shows how convection and buoyancy work under 1g. Gas bubbles and hot water moves towards the top of the container. Under µg conditions the gas bobble stays at the bottom of the container and the heat is transported only by heat flow caused by the temperature gradient (and not by stirring).





(3) Surface phenomena, capillary rise etc

→ liquid transport in capillary structures
(networks like cellulose, 'soil' etc)
→ uptake processes by plant roots
→ surface, bubble phenomena etc



Stirring and mixing, convection are very important phenomena. Key words

→ diffusion controlled mechanisms
→ transport over membranes
→ coupling between cells
etc

Parenthesis: Electrochemical potential μ

$$\mu = \mu_0 + RT \ln c + \bar{V} \cdot P + zF\psi + \rho g h + \ldots$$

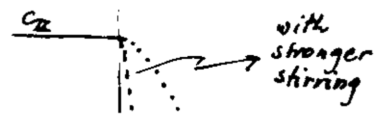
Transport occurs across a membrane etc when $\mu_I \neq \mu_{II}$
or, more general, when $\operatorname{grad} \mu \neq 0$

$$\operatorname{grad} \mu = RT \frac{1}{c} \cdot \operatorname{grad} c + \bar{V} \cdot \operatorname{grad} P + zF \operatorname{grad} \psi + \rho g \operatorname{grad} h$$

↓ diffusion ↓ bulk flow ↓ ionic flow $= 0$ in space

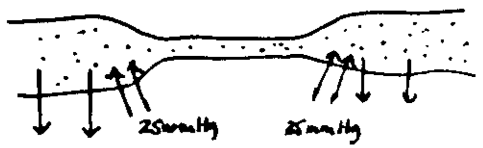
$$\text{Flux} = \phi = -(\text{mobility}) \times c \times \operatorname{grad} \mu$$

Stirring effects (example)



$$\text{grad}\,\mu = \underline{RT\frac{1}{c}\,\text{grad}\,c} + \underline{\bar{V}\cdot\text{grad}\,p}$$

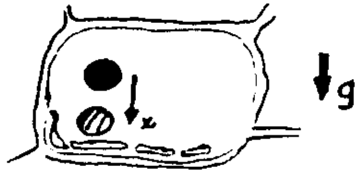
Example: capillary



Between physics and biology: the balance system as an example.

Discuss sedimentation and movements of a mass perceptor in a (plant) cell.

* Statolith (lithos' = stone) otholiths in man
* gravitropism



Bio physical approach

$$\Delta m\cdot\ddot{x} = \Delta m\cdot a - 6\pi R\eta\dot{x}$$

Stokes' law

free fall of spherical particle

Solution: $v(t) = k\cdot a\left[1-e^{-t/k}\right] + v_0\,e^{-t/k}$

$$x(t) = x_0 + k\left[a\cdot t + (v_0 - a\cdot k)(1-e^{-t/k})\right]$$

Simplified: $\boxed{\Delta m\cdot g = 6\pi R\eta\cdot v_{end}}$

$$k = \frac{\Delta m}{6\pi R\eta}$$

Formulae used in the literature!

Uncertainties regarding $\Delta\rho$ $(0.3\, g/cm^3)$

R $(1\,\mu m)$

η $(0.02\, Ns/m^2)$

<u>What is the smallest distance which can possibly be detected?</u> ask the physicists

physical phase → physiological reactions → growth reactions to correct deviation

Assume that the ultimate limit for detection lies in the first block and that it is <u>thermal noise</u>

The change in energy in the sedimentation process must then be $\geq kT$

$$\Delta x \cdot \Delta m \cdot g \geq kT \qquad (1)$$

Assume Stokes' law to be valid

$$\Delta m \cdot g = 6\pi R \eta \frac{\Delta x}{\Delta t} \qquad (2)$$

Δt is then the shortest time necessary for detectability.

we then get

$$\Delta x = \frac{\Delta m \cdot g \cdot \Delta t}{6\pi R \eta} \qquad (2')$$

which gives in (1)

$$\Delta t \geq \frac{kT \cdot 6\pi R \eta}{(\Delta m \cdot g)^2}$$

parameter values mentioned before gives $\Delta t \approx 25\, s$. If N particles $\Rightarrow \Delta t \approx 25/N$, i.e. seconds!

Experimental results difficult to get on earth, but results indicate $\Delta t \leq 10-30\, s$

Would be ideal to do an experiment when the force is $< 1 \times g$!

NB! Mass perceptor can not be IAA (indole acetic acid) which is a small molecule with $M \approx 180$!

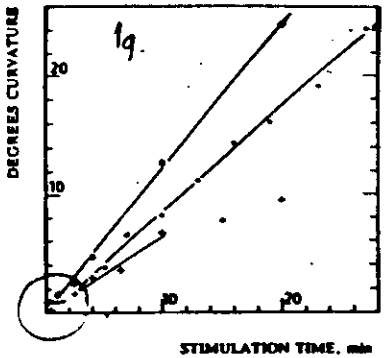


Figure 5: *Bending reactions in oat plants receiving 1 g stimulations for different stimulation times in horizontal position. (●) From Pickard 1973, 25 °C, extrapolated threshold time 20 s. (●) and (+) from Johnsson 1971, 22.5 °C, measured in two different directions X and Y (cf. Figure 3). Standard deviation roughly 1 degree.*

what is the actual limit for stimulation to be perceived ?

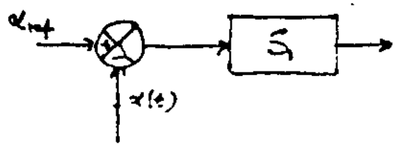
⇒ experiments at lower g-levels !

Another biophysical approach: systems analysis

Input - output relations of linear systems (Laplace-transformations etc.)

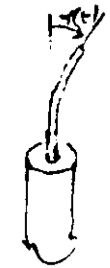
Input - output relations of non-linear systems in biology.

Black box analysis of the (gravitropical) balance system.



$$\dot{\alpha}_1 = \text{constant} \cdot \sin(\alpha_{ref} - \alpha(t))$$

dependent on g !



α_{ref} often plumb line $(=0)$

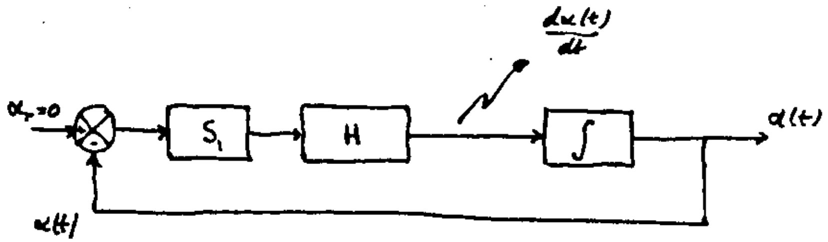
To sum up many physiological reactions in a kind of 'minimum' model we assume that

reaction (t) = sum of weighted earlier stimulations.

$$\frac{d\alpha(t)}{dt} = -\sum h_i \sin\alpha(t_i) = -\int_{t}^{\infty} h(x)\cdot \sin\alpha(t-x)\,dx$$

$h(x)$ is a weighting function

We then get



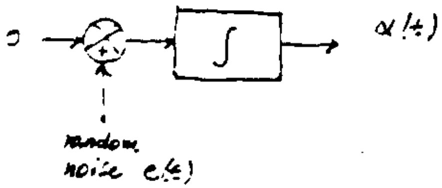
balance system as a feed back system obvious

In fig S_1 will be zero and no feed back! External stimulations →

Simulations can be carried out to identify parameters etc.

Noise will certainly be present in the system - at different positions.

A particularly simple example reminds us of the Brownian movements! (random walk).



Thus,
$$\frac{d\alpha(t)}{dt} = e(t) \qquad \text{error}$$

$$\alpha(t) - \alpha(0) = \int_0^t e(s)\,ds$$

for mean zero white noise (and $\alpha(0)=0$)

$$\overline{\alpha(t)} = \overline{\int^t e(s)ds} = \int^t 0\,ds = 0$$

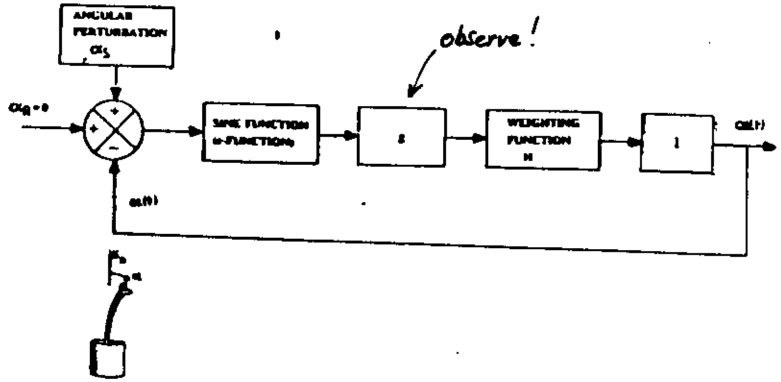


Fig. 5. Feedback system to describe gravitropical reactions. External gravitropic stimulations are introduced as perturbations α_s. The actual angle of the plant is compared with the reference input α_R (= plumb line direction). This error signal is then the input to the gravitropical system represented by the SINE FUNCTION, g, WEIGHTING FUNCTION and I blocks. The different blocks are described in the text.

General minimum model for balance system.

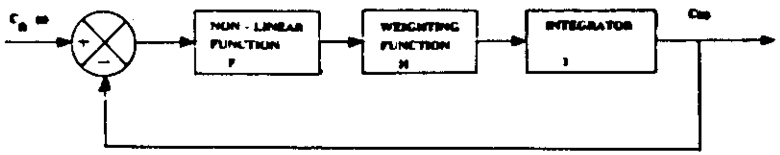


Fig. 2. A feedback system to regulate the time varying concentration C(t) e.g. inside a cell. The concentration C(t) is compared with the reference concentration $C_b(t)$. The error signal is the input signal to the blocks F and H containing a non-linear function and a weighting function, respectively. The output signal from the H block is the rate of change of the concentration, dC(t)/dt. An integration is necessary to calculate the actual concentration and the feed back loop can be closed.

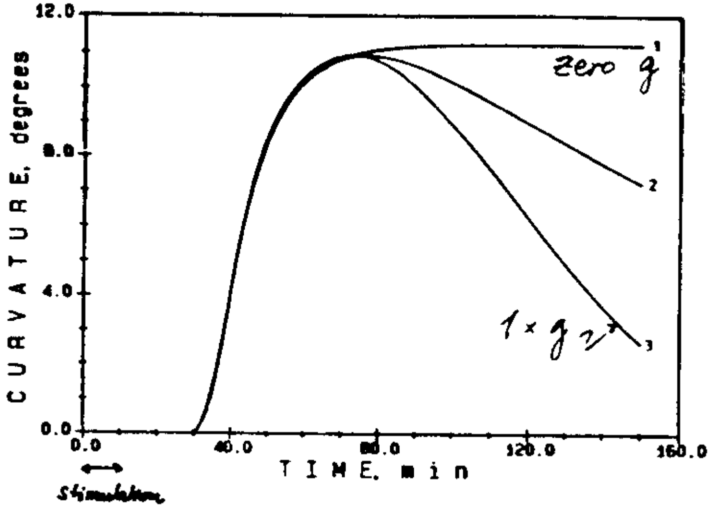


Fig. 6. Simulations of the gravitropic response when different treatments have been introduced to the plant after the stimulation period. In curve (1) the plant is kept upright at 0 g after the stimulation. In curve (2) the plant is clinostated with an asymmetric ε-function (specified in Fig. 7). In curve (3) the plant is kept upright at 1 g after the stimulation.

But $\qquad \overline{\alpha^2(t)} = \int_0^t e(s)\,ds \int_0^t e(s')\,ds'$

Assume $e(s)$ to consist of random steps α, different in direction but with equal magnitude

$$\overline{\alpha^2(t)} = \overline{\left(\sum_{i=0}^{n} \alpha_i\right)\left(\sum_{0}^{n} \alpha_i\right)} = \overline{\alpha_1\alpha_1} + \overline{\alpha_1\alpha_2} + \quad + \overline{\alpha_1\alpha_n}$$

$$\vdots$$

$$\overline{\alpha_n\alpha_1} + \overline{\alpha_n\alpha_2} + \quad + \overline{\alpha_n\alpha_n}$$

$$= n \cdot \alpha^2$$

With ν steps pr. unit time we get $n = \nu \cdot t$ and

$$\overline{\alpha^2(t)} = \nu \cdot \alpha^2 \cdot t = \text{constant} \cdot t$$

(can be improved! but important that the prediction is that the mean square value is proportional to time t (as for Brownian movement, diffusion). Can we test?

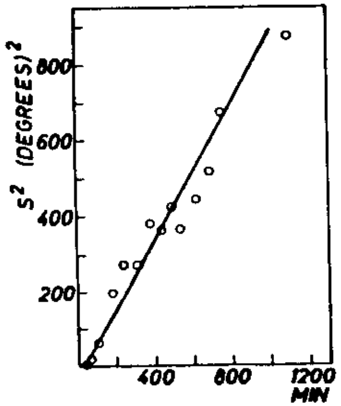
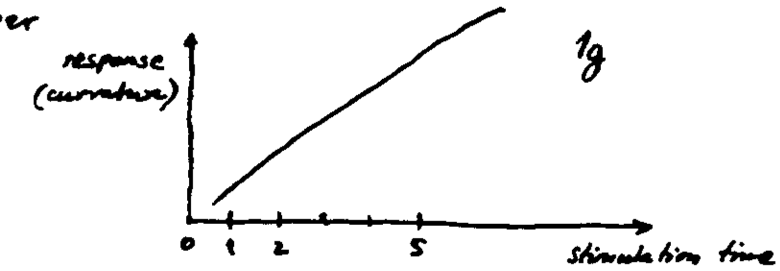


Figure 4. *Curvatures of Artemisin roots* (recalculated from measurements by Larsen 1957, Figure 16 curve C). The spontaneous curvatures are plotted as the squared standard deviations versus the time (cf. Figures 2 B and 3 B). It is noted that the values confirm, also in this case, a linear relation between time and the mean square of the deviation.

A Space experiment to study some fundamental properties of the balance system. A case study.

Remember



* Is there a threshold stimulation time?

* How does corresponding curves for other forces look like?

  (Is the dose $= \int F \cdot dt$ determining the response so that, e.g., 0.2g ×10 min gives the same response as 2g × 1 min?)

Let us go down in the force region between 0 and 1g
Possible in Space with centrifuges.

The aim of the experiment GTHRES on the IML-1 flight in Febr 1991

PI	Allan Brown,	Univ of Pennsylvania
CI	David Chapman,	Univ of Pennsylvania
	Anders Johnsson,	Univ of Trondheim

How to carry out GTHRES?
Some steps:

1. Grow small oat plants under 1g.
   → req. growth centrifuge

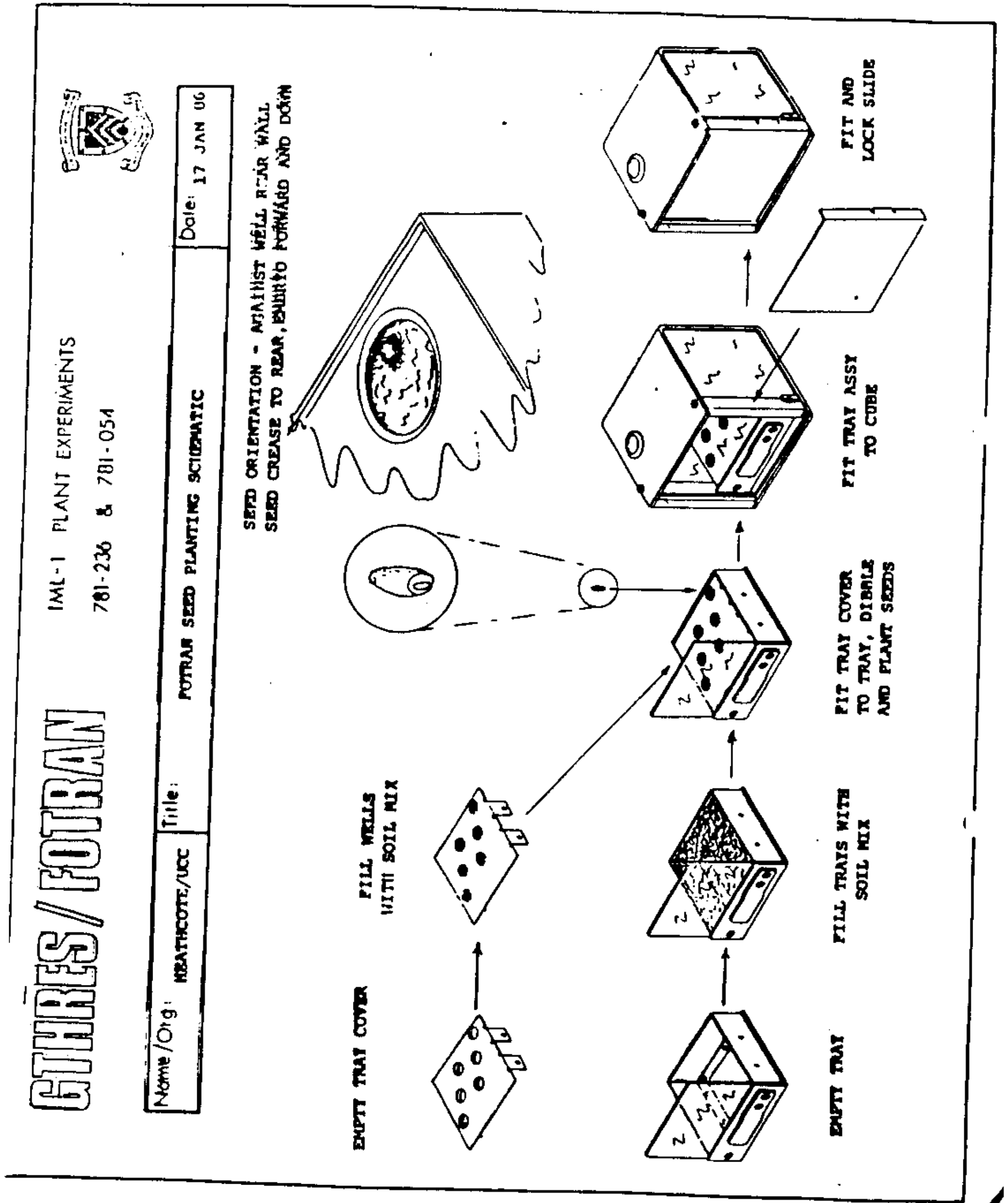
2. Take a photo of plants
   → req. growth chambers
   CCD - cameras
   video recorders

3. Stimulate plants perpendicularly to shoot at predetermined force and for chosen stimulation time
   → req. test rotors
   electronic control system

4. Take photos at regular time intervals

5. Extract responses (curvatures) and plot results from photos
   → req. image processing system
   data handling.

Hardware and results from Investigator Ground Studies can be seen on some slides



SEQ.	TEST TIME	TIME	DATE	DIR BY	ACT BY	DESCRIPTION	DATA	VERIF. OPER	QA
13-011	T-2:22:30	9:30am	6/3	TC	TS	Perform Pre-Operation Set-Up Instructions 6 - Rack Power System (RPS) Set-Up.			
13-012	T-2:10:00	10:00pm	6/3	SR	PI	Plant seeds for GTHRES group 13. Perform Operation Instructions 2 - Plant GTHRES Seeds.			
13-013	T-2:04:00	4:00am	6/4	SR	PI	Plant seeds for GTHRES group 14. Perform Operation Instructions 2 - Plant GTHRES Seeds.			
13-014	T-2:00:30	8:30am	6/4	SR	PI	Plant seeds for FOTRAN group 16. Perform Operation Instructions 1 - Plant FOTRAN Seeds.			
13-015	T-1:10:00	10:00pm	6/4	SR	PI	Plant seeds for GTHRES group 15. Perform Operation Instructions 2 - Plant GTHRES Seeds.			
13-016	T-1:04:00	4:00am	6/5	SR	PI	Plant seeds for GTHRES group 16. Perform Operation Instructions 2 - Plant GTHRES Seeds.			
13-017	T-1:00:30	8:30am	6/5	SR	PI	Plant seeds for FOTRAN group 17. Perform Operation Instructions 1 - Plant FOTRAN Seeds.			
13-018	T-0:01:00	7:00am	6/6	TC	TS	Turn on RPS in accordance with 1-T-003, Vol. II Allow 30 minute warm-up for RPS to stabilize.			
13-019	T-0:00:30	7:30am	6/6	TC	TS	Set the following values on the RPS: 1. DC voltage alarm, high = 30 volts ____ 2. DC voltage alarm, low = 26 volts ____ 3. DC current alarm, high = 40 amps ____ 4. DC current alarm, low = 1 amp ____ 5. DC voltage output = 28 volts ____ 6. Digital alarm switch = DISARM ____ 7. 28 VDC supply = ON ____			
13-020	T-0:00:30	7:30am	6/6	TC	DR	Initialize SEI in accordance to Procedure 1-D-001.			

II:5

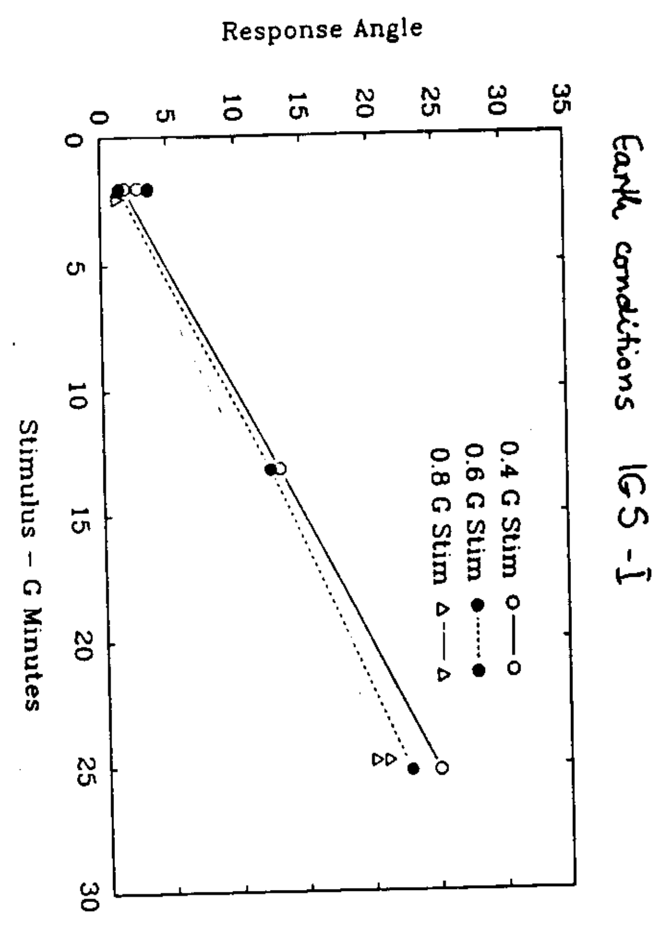


Figure 3.6 A test of the Reciprocity Rule with maximum response curves at 0.4, 0.6 and 0.8 g.

GTHRES (g-threshold) TIME-ASPECTS

ANNOUNCEMENT OF OPPORTUNITY (BROWN, CHAPMAN, JOHNSSON)	Febr '78 (NASA)
PROPOSAL SUBMITTED	June '78 (NASA)
EXPT ACCEPTED FOR DEVELOPMENT	Dec '80 (NASA)
LAUNCH DATE	~~1985~~
	~~1987~~
	~~1991~~
	June ~~1990~~
	Febr ~~1991~~
	To Be Determined
	~~April~~ 1991
	Febr 1991

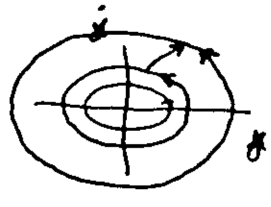
Oscillatory biological systems. Some aspects on their behaviour in space.

Oscillations e.g. $\ddot{y} + \omega_n^2 y = 0$ linear ones!

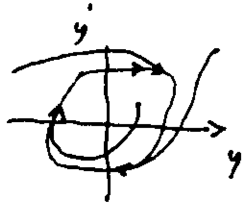
Non-linear oscillations in biology, e.g., the van der Pol's eqn.

$$\ddot{y} + \varepsilon (y^2 - 1)\cdot\dot{y} + \omega_n^2 \cdot y = 0$$

it has a limit cycle



pendulum



For a moment, go back to the balance system of plants

$$\frac{d\alpha(t)}{dt} = -\int_{0}^{\infty} h(x)\cdot \sin\alpha(t-x)\,dx$$

simplified:

$$\frac{d\alpha(t)}{dt} = -k\cdot\alpha(t-t_0)$$

check with $\alpha = \alpha_0 e^{i\omega t}$

($h(x) = \delta(t_0)$ and small angles!)

This integral-difference equation, which thus corresponds to a simplified feed back system, can very well oscillate (with a period $\tau \approx 4t_0$.)

A feedback system oscillates if

* the amplification is big enough ('k')
* the time delay, or phase change, is big enough ('t_0')

So simulations should, for certain parameter values, show oscillations

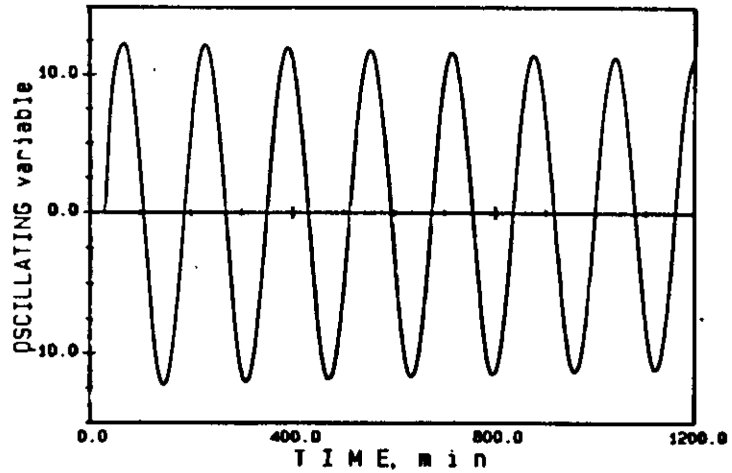


Fig. 3. Simulation of the oscillatory behavior of a feedback system (the system could be as described in Fig. 2 or 5). A stimulation pulse was given at the start of the simulation to trigger the oscillations.

t_0 τ

Circumnutations of sunflower seedlings
(under $1 \times g$ and $3 \times g$)

Movements seen from the side:

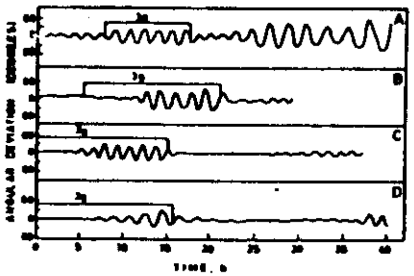


Fig. 3. Circumnutations under changes of the g-values experienced by the hypocotyls. Changes between 1 g and 3 g were introduced at different ages of the hypocotyls. The g-value was 1 g, interrupted by 3 g intervals as indicated at the top of the recordings. Recordings as in Fig. 1

From above:

Conclusion: Circum-nutations influenced by gravity?

How do the circumnutations behave in space?

Hypothesis	Origin of nutations	Prediction
1.	Oscillations in a gravitropic feedback system; dependent on $\vec{g}$	Stop at μg.
2.	'Internal' oscillations not connected with g-force; unknown origin	Continue unaffected by μg
3.	Internal oscillator but movements coupled to and amplified by gravitropic system	Diminished amplitude but slight movements in μg.

Centrifuge expts speak against 2.

The Space experiment HEFLEX in Spacelab-1 tested the predictions. # 3 seems to be correct

Origin of internal oscillators??

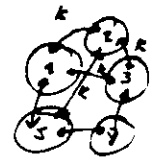
Let us come back to long term rhythms with a period, τ, of about 24h (circadian rhythms or biological clocks).

They exist in cells which are eukaryotic (have cell nucleus etc), both in unicellular and multicellular organisms.

In one and the same organism they are usually synchronized to each other, they are coupled.

The coupling between self-sustained oscillators affect the period; look at circadian rhythm of multi oscillatory system!

Illustrative, simplified example



all oscillators identical
all coupling coefficients identical

$$\ddot{y}_i + \omega_n^2 y_i = 0$$ "natural frequency ω_n"

with coupling

$$\ddot{y}_i + \omega_n^2 y_i = k \cdot \sum_{\substack{j=1 \\ j \neq i}}^{n} y_j$$

that is

$$\begin{cases} \ddot{y}_1 + \omega_n^2 y_1 = k \sum_{2}^{n} y_j & = k \sum_{1}^{n} y_j - k y_1 \\ \vdots & \\ \ddot{y}_n + \omega_n^2 y_n = k \sum_{1}^{n-1} y_j & = k \sum_{1}^{n} y_j - k y_n \end{cases}$$

Look at the overall variable $Y = \sum_{1}^{n} y_j$

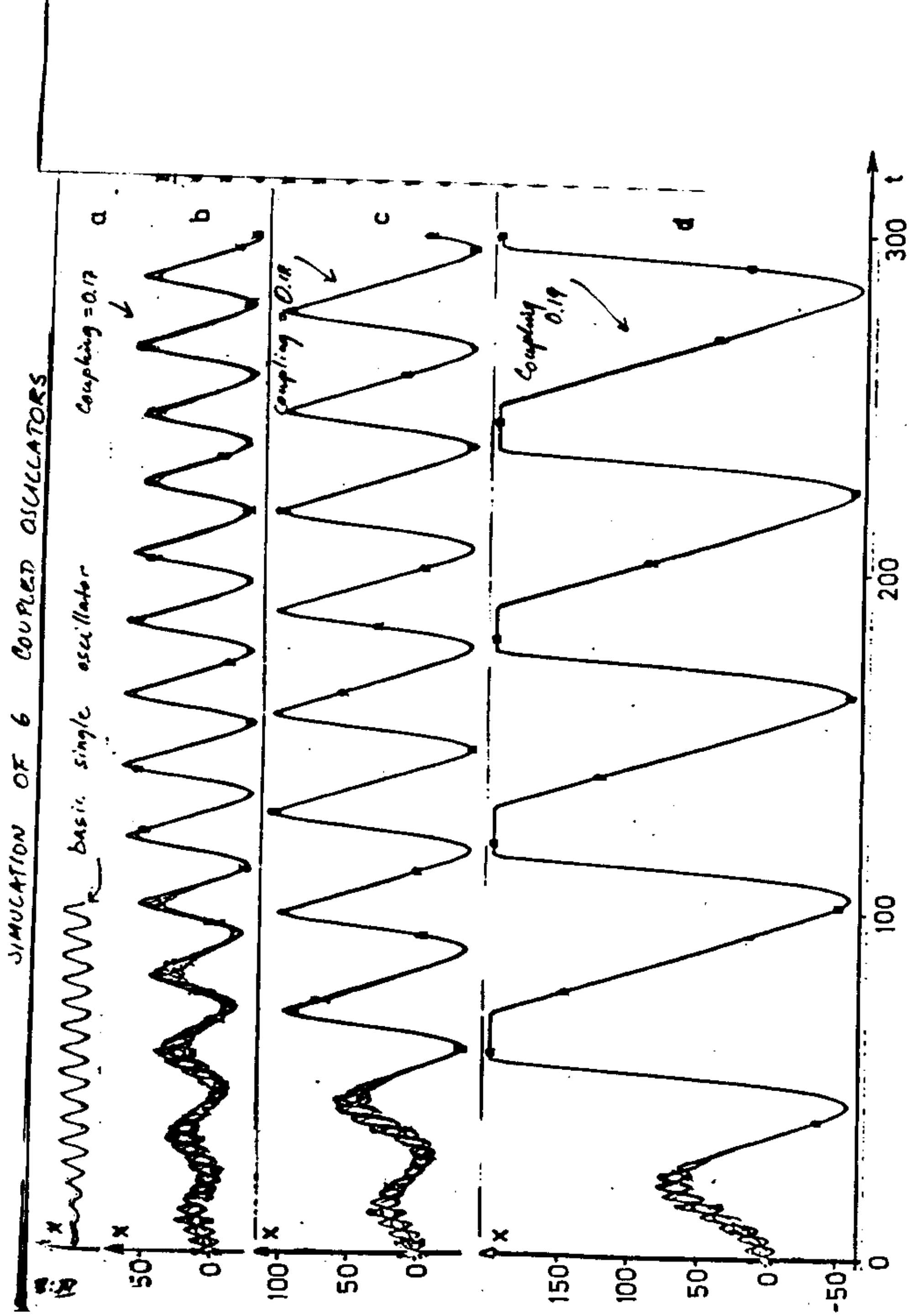
Sum up to get $\ddot{Y} + \omega_n^2 Y = k \cdot n Y - k Y$

or $\ddot{Y} + \left(\omega_n^2 - k(n-1)\right) \cdot Y = 0$

for the coupled system, therefore,

$$\omega_{\text{coupl}}^2 = \omega_n^2 - k(n-1)$$

the coupling, k, influences the frequency also in the non-linear case!



In humans we have at least two groups of oscillators!

Important questions – also in μg!

* how do rhythms – especially circadian rhythms – behave in Space?
* are multicellular organisms showing rhythms with a different period in Space?
* is μg affecting the coupling between the cells and the rhythms?

Interface between physics and biology

It is a particularly rich field on Earth and will be so in Space

We have just covered a few aspects:

* where do we know that μg will play a rôle? (sedimentation, stirring etc)
* balance systems studies
* systems analysis in general
* oscillatory systems

etc.

But I have not discussed many other areas where physics and biology must join:

* biology under extreme vacuum
* radiation biology in Space
* biophysics of closed ecological systems in Space (plant/man systems)
* synergistic effects of electric fields, magnetic fields etc and μg
* vibration sensitivity of biological systems (tolerance limits)
* adaptation to new g-levels and its biophysics