12 GGonGround - Extended Synopsis

The science case. *General Relativity* (GR) is the best theory of gravity to-date. It governs physics at the macroscopic and cosmic scales and has been highly successful. However, all attempts at merging gravity with the other forces of nature have failed and most of the mass of the universe is unexplained.

General Relativity is based on the hypothesis that the gravitational force is composition independent: in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition. This property is unique to gravity. It is referred to as the *Universality of Free Fall* (UFF) and it is a direct consequence of the *Equivalence Principle* (EP). It was first subject to experimental proof by Galileo in Pisa. Newton regarded testing it as so important that reported the results of his own experiments "*very accurately made*" in the opening paragraph of the *Principia* to justify the assumption that "*mass*" and "*weight*" are equivalent –i.e. the equivalence between inertial and gravitational mass. Einstein went much further and stated what he later referred to as the "*happiest thought of my life*": if all bodies fall equally fast, in a freely falling frame gravity has –locally– no dynamical effects. UFF is therefore equivalent to making the "*hypothesis of complete physical equivalence*" between a gravitational field and an accelerated frame([1], Ch. V *"Principle of relativity and gravitation"*, Sec. 17 *"Accelerated reference system and gravitation"*). Starting from this hypothesis –published in 1907– by extending it globally, 9 years later Einstein formulated the *General Theory of Relativity*, which is therefore founded on the UFF. Any violation of UFF (hence of EP) would violate General Relativity as well as all metric theories of gravity.

UFF experiments are unique tests of General Relativity in that –unlike all others– they address the assumed composition independence of gravity which sets it aside from all other forces of nature; this fact makes them the most deeply probing tests in the search for new physics beyond General Relativity and the current *impasse*.

In the scientific community at large it is recognized that experimental evidence of a violation of the UFF (hence of EP) would make for a scientific revolution.

State of the art. Very stringent limits to the validity of UFF and EP have been set by small size experiments in which the test masses are mechanically coupled by means of a very sensitive torsion balance which is also slowly rotating. These experiments have reached a sensitivity to differential acceleration between the test masses of $\simeq 1.69 \cdot 10^{-15}\,\mathrm{ms}^{-2}$, finding no violation in the field of the Earth to the remarkable level $\eta = 10^{-13}$ [2], η being the fractional differential acceleration of the test masses w.r.t. the Earth (their average acceleration in the horizontal plane of the lab at the latitude of the lab is $\simeq 1.69 \cdot 10^{-2}\,\mathrm{ms}^{-2}$). Despite the much larger free fall acceleration, Galileo-like mass dropping tests have been by far less sensitive than torsion balances. The reasons are twofold: a time of fall of just a few seconds and the test masses release errors.

Careful physical modeling and analysis of laser ranging data to the corner cube reflectors left on the surface of the Moon by the Apollo missions have set a limit similar to that of torsion balances for the Moon and Earth falling in the gravitational field of the Sun[3].

However, although a violation is expected at some point, no firm prediction exists as to the precise level at which it should occur.

Laboratory controlled experiments with slowly rotating torsion balances have reached the level of thermal noise ([4], Fig. 20); lunar laser ranging tests are close to their limit[5]. Even one order of magnitude improvement may be difficult with those techniques. As for new tests based on dropping cold atoms, they have achieved 10^{-7}, i.e. they are 6 orders of magnitude less sensitive than tests based on macroscopic bodies[6]; and they have yet to match the best result $\Delta g/g \simeq 3 \cdot 10^{-9}$ obtained in measuring the local gravitational acceleration by dropping a single species of atoms[7].

It is apparent that a radically new type of experiment is necessary to improve the current experimental limit in UFF and EP tests by several orders of magnitude thus deeply probing this physical domain so far unexplored.

The case for a test of UFF and EP in low Earth orbit. Back in the 1970s it was realized that a torsion balance kind of experiment in which two weakly coupled test masses orbit the Earth inside a low altitude spacecraft would be equivalent to dropping them from an "infinitely" tall tower, thus yielding both a stronger signal from Earth (by about 3 orders of magnitude) and a time of fall around it as long as the mission duration (and no mass release problems). A violation signal (pointing to the center of the Earth) would appear at the (low) orbital frequency of the satellite –of a few 10^{-4} Hz– to be upconverted to higher frequency by rotation of the spacecraft in order to reduce noise ([8], [9], [10]). Absence of weight and isolation of the laboratory (the spacecraft) are additional great advantages. Overall, in low Earth orbit an improvement by 4 orders of magnitude, down to $\eta = 10^{-17}$, is within reach and the idea has attracted the interest of NASA and of other space agencies later on.

At an orbiting altitude $h \simeq 600\,\mathrm{km}$ where the attraction from the Earth is $g(h) \simeq 8\,\mathrm{ms}^{-2}$ it requires to detect a differential acceleration of the test cylinders relative to each other as small as $a = \eta\, g(h) \simeq 8 \cdot 10^{-17}\,\mathrm{ms}^{-2}$. If they are coupled with a natural differential period of oscillation T_d, the corresponding relative displacement to be measured by the read out is $r = a\,(T_d^2/4\pi^2)$ (at the satellite orbital frequency); the weaker is the coupling, the longer is the differential period, the more sensitive is the accelerometer.

The case for "Galileo Galilei" (GG) to test UFF and EP to 10^{-17}. All investigators agree that the proof masses in space should be "concentric" cylinders –with the centers of mass as close as possible to each other to reduce classical differential (*tidal*) effects due to the non uniformity of the gravitational field– and should rotate, in order to upconvert the signal to higher frequency –the higher the better. The question is: should the concentric test cylinders be sensitive (i.e. weakly coupled) along the symmetry axis (1D accelerometer) and rotate around an axis perpendicular to it, or else should they rotate around the symmetry axis and be sensitive in the plane perpendicular to it (2D accelerometer)?

Although spinning around an axis which is not the symmetry axis is unnatural, the choice of coupling the test cylinders in 1D prevailed, despite the fact that it essentially rules out fast rotation because it is well known that forcing an oscillator above its natural frequency causes the forcing signal to be attenuated. Overall, this choice made it necessary to solve the main critical issues of a high sensitive space experiment by brute force, most notably by requiring that the experiment be carried out in cryogenic conditions, close to absolute zero temperature [11].

The signal to be measured asks for both weak coupling and fast spin, a situation which is known as *rotation in supercritical regime*: it makes fast rotation possible through autocentering, but it is well known that it cannot work in 1D –it works only if coupling occurs in 2D ([12], [13]). The "Galileo Galilei" (GG) space experiment was proposed in the mid 1990s by A. M. Nobili and colleagues who realized taht this choice makes most of the critical issues disappear by design: fast rotation does not attenuate the expected low frequency signal; the centers of mass of the test cylinders center on each other by the laws of physics; most dangerous effects become DC; the experiment does not require cryogenics; fast rotation and cylindrical symmetry allow passive 1-axis stabilization of the spacecraft and significantly reduce its size and complexity; etc... ([14], [15]).

Strong arguments have been published in support of the novel idea of a differential accelerometer sensor with the proof masses weakly coupled in 2D (rather than along a single direction as in all previous attempts) and rotating faster than their natural oscillation frequency ([16], [11], [17]). The GG space experiment has been investigated by ASI (Agenzia Spaziale Italiana) ([]). More importantly, the new sensor design allows a full-size 1-g version of it –with the same number of degrees of freedom and the same dynamical features– to be built and tested on ground: the symmetry axis of the concentric test cylinders is in the vertical direction, they are suspended and spin around it while being weakly coupled in the horizontal plane of the lab. GG on Ground (GGG) has been set up with funding from ASI and INFN ([18], [19], [20], [21]); the latest experimental results reported in Fig.1 demonstrate that weak coupling and sensitivity to very small forces are compatible with rapid rotation; indeed, it is rapid rotation that makes sensitivity to small forces possible.

The most relevant physical property of the GG novel sensor has been demonstrated in 2011 [22]: thermal noise due to inetrnal damping and competing with the low frequency signal of interest is reduced as $1/\sqrt{\nu_{spin}}$ (with no signal attenuation) making rapid rotation more effective than cryogenics to reduce thermal noise. Recent collaboration with JPL (Jet Propulsion Laboratory, CalTech-NASA) has shown that an optical read-out based on the very low noise laser interferometric gauge developed

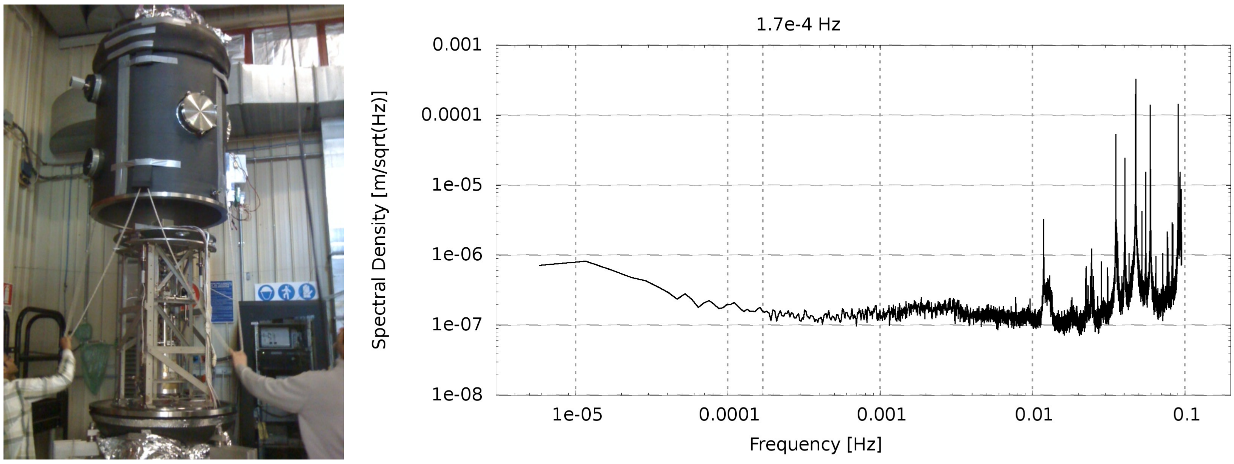

Figure 1: *Left:* the GGG experimental apparatus (at INFN lab in San Piero-Pisa, built with funding from ASI and INFN) while opening the vacuum chamber. The test masses are concentric hollow cylinders (10 kg each) with the symmetry axis in the vertical direction, weakly coupled in the horizontal plane by means of high quality $CuBe$ joints in 2D. Together they form a very peculiar beam balance in which the beam is vertical –hence the balance is sensitive to differential forces in the horizonal plane– and the masses of the balance are concentric. The relative displacements of the test cylinders in the horizontal plane are read by 2 orthogonal capacitance bridges whose plates are located halfway in between them. The balance rotates around the vertical axis so that low frequency forces are upconverted to the spin frequency. The rotating shaft is held by ceramic ball bearings. An additional 2D weak joint is located just below the bearings in order to reduce low frequency tilts and horizontal accelerations due to terrain microseismic noise and bearings noise on the shaft. Note that both terrain and bearings noise are absent in the space experiment because the spacecraft is isolated (no terrain) and after its initial spin up by the launcher no motor or bearings are needed thanks to angular momentum conservation. *Right:* Linear spectral density of the relative displacements of the test cylinders in the horizontal plane of the lab in a 20 d run (still ongoing) after demodulation from the rotating frame ($\nu_{spin} = 0.19\,\mathrm{Hz}$). The frequency of interest is the orbital frequency of the GG satellite $\nu_{GG} = 1.7 \cdot 10^{-4}\,\mathrm{Hz}$ at which a signal is expected in space in case of violation of the universality of free fall and the equivalence principle in the field of the Earth. At ν_{GG} the measured displacement noise is $2 \cdot 10^{-7}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; after integrating for 30 d and with a coupling natural oscillation period of 10 s, the differential acceleration noise –at this frequency– is $8.5 \cdot 10^{-11}\,\mathrm{ms}^{-2}$.

and demonstrated at JPL will allow GG to fully exploit the very short integration time which derives from the novel design of its sensor; it means that a full test to 10^{-17} can be performed in just 1 day of integration (taking into account also damping due to residual gas and eddy currents[23]). In a 9-month mission all necessary checks against systematics can be performed so that the question as to whether the result is new physics or else it is due to a tiny known disturbance –hence it is a null result– can be established beyond doubt[24]. The collaboration has led to an agreement between JPL and ASI to submit GG to the EXPLORER program as a NASA led mission and the partnership of ASI, with Mike Shao (JPL) as PI and Anna M. Nobili as Co-PI. EXPLORER is a long time program of NASA dedicated to flying small size missions to be realized in a few years; the Nobel prize winner COBE was one of them. The 2010 Decadal Astronomy has ranked the EXPLORER program as its second highest priority and has advised NASA to further strengthen it

The case for GGonGround and the importance of working in synergy. GG is a high precision physics experiment which can reach its final sensitivity and meet its outstanding science goal only in orbit, but that is just the final run of an experiment whose performance can and must be tested and demonstrated in the lab. The EXPLORER program is the only possible route to space for GG, but for GG to win in the EXPLORER competition the GGG lab experiment must prove –by sufficiently isolating the sensor from ground noise sources and with an adequate read out– that the sensor in space can meet its target. Synergy between the Pisa PI A. M. Nobili, who has led GG and GGG so far, and the Ferrara PI G. Zavattini who will lead the efforts for implementing a low noise laser gauge read out can dramatically improve GGG because there are no fundamental limitations. As shown in Fig.1 the current GGG apparatus has demonstrated (at the GG signal frequency) a sensitivity of $8.5 \cdot 10^{-11}\,\mathrm{ms}^{-2}$ in 30d while GG should reach $8 \cdot 10^{-17}\,\mathrm{ms}^{-2}$ to meet its goal. The noise budget reported in Table 2 shows that GGonGround project can improve this sensitivity to $\simeq 8 \cdot 10^{-16}\,\mathrm{ms}^{-2}$. This requires to further reduce the bearings and local terrain noise (both absent in the space experiment), and to implement a laser gauge read out replacing the current capacitance read out. We see no show stoppers. The roadmap Table 3 shows that this can be done in steps within the first 3 years of the project, to secure the success of GG in the first part of the EXPLORER selection process. The remaining 3 years will be devoted –as detailed in Table 3– to bridging the remaining gap with the laser gauge noise required in space and to manufacturing and testing specific components of the space sensor itself to ensure the success of the space mission and to strengthen the European contribution to it.

The case for EGO as Host Institution. EGO (European Gravitational Observatory) appears as the best Institution to host a Synergy Grant project in experimental gravitation. GGonGround needs a specific but limited laboratory space (roughly $50\,\mathrm{m}^2$ with about $6\,m$ high roof) where the current apparatus and equipment (acquired with ASI and INFN funds) will be moved. All GGonGround activity will be carried out by the two PIs and their collaborators.

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GGonGround goal vs GG goal in space				
	Differential acceleration between test masses a @ $1.7 \cdot 10^{-4}$ Hz	$a\,[\mathrm{ms}^{-2}]$	$r = a\frac{T_d^2}{4\pi^2}$ [m]	Integration time T_{int} [d]
GG goal in space	$a_{GG} = \eta g(h)$ (upconverted to 1 Hz)	$8 \cdot 10^{-17}$ ($\eta = 10^{-17}$, $h \simeq 600\,\mathrm{km}$)	$6 \cdot 10^{-13}$ ($T_d \simeq 540\,\mathrm{s}$)	1
GGonGround goal	$a_{GGG} = 10 a_{GG}$ (upconverted to $0.2 \div 3$ Hz)	$8 \cdot 10^{-16}$	$3.2 \cdot 10^{-14}$ ($T_d \simeq 40\,\mathrm{s}$)	30

GGonGround noise budget @ $1.7 \cdot 10^{-4}$ Hz					
Noise Source	Δa $[10^{-13}\,\frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}}]$	Integrated Δa ($T_{int} = 30$ d) $[10^{-16}\mathrm{ms}^{-2}]$	Δr ($T_d \simeq 40$ s) $[10^{-11}\,\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}]$	Integrated Δr ($T_{int} = 30$ d) $[10^{-14}\mathrm{m}]$	Conditions and physical data
Tilt noise sources: $a_{tilt} = \frac{k_c}{mgL}\frac{k_{shaft}}{M_{tot} g L_{shaft}} g\theta_{tilt}$					
terrain	8.2	5.1	3.3	2.1	$\theta_{terrain} \simeq 8 \cdot 10^{-6}\,\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$
air bearing	4.1	2.5	1.7	1.0	$\theta_{ab} \simeq 4 \cdot 10^{-6}\,\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$ $k_c \simeq k_{shaft} \simeq 0.04\,\mathrm{Nm/rad}$ $m = 10\,\mathrm{kg}$ $L = 0.5\,\mathrm{m}$ $M_{tot} \simeq 80\,\mathrm{kg}$ $L_{shaft} \simeq 4\,\mathrm{m}$
Thermal noise sources[22],[23]					
suspensions	1.3	0.8	0.5	0.3	Q=20000, $\nu_{spin} = 0.2$ Hz
eddy currents	1.3	0.8	0.5	0.3	no μmetal magnetic shield
residual gas	0.5	0.3	0.2	0.1	2 cm gap, P = 10^{-4} Pa
ReadOut noise: $a_{ROnoise} = (4\pi^2/T_d^2) r_{ROnoise}$					
laser gauge	7.4	4.6	3.0	1.8	$T_d \simeq 40$ s
Total noise	12	7.4	4.8	3.0	

Table 2: GGonGround goal and noise budget

GGonGround Roadmap		
Time (Months)		
		Performance achieved
	t_0	$a_0 = 8.5 \cdot 10^{-11}\,\mathrm{ms}^{-2}$ (INFN lab San Piero, Pisa; ASI and INFN funding; Fig. 1)
		First 18–month period targets
6	$t_0 + 6$	$a_1 = 2.8 \cdot 10^{-12}\,\mathrm{ms}^{-2}$ ($T_d = 14.8\,\mathrm{s}$ $\mathrm{r_{capRO}} = 1.45 \cdot 10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; can be done with capacitance read out and ball bearings, requires weaker joints by a factor 4)
12	$t_0 + 12$	$a_2 = 7.7 \cdot 10^{-14}\ ms^{-2}$ ($T_d = 40\,\mathrm{s}$ $\mathrm{r_{capRO}} = 3 \cdot 10^{-9}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; can be done with capacitance readout and ball bearings, requires 10 times longer suspension shaft)
18	$t_0 + 18 = t_1$	$a_3 = 5.6 \cdot 10^{-15}\,\mathrm{ms}^{-2}$ ($T_d = 40\,\mathrm{s}$ $\mathrm{r_{laserRO}} = 2.2 \cdot 10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; requires preliminary version of air bearings and laser metrology)
		Second 18–month period targets
24	$t_1 + 6$	reduce air bearings and rotation noise
30	$t_1 + 12$	reduce laser gauge read out noise
36	$t_1 + 18 = t_2$	$a_4 = 7.7 \cdot 10^{-16}\,\mathrm{ms}^{-2}$ ($T_d = 40\,\mathrm{s}$ $\mathrm{r_{laserRO}} = 3.0 \cdot 10^{-11}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; requires air bearings to full performance and improved laser metrology)
		Third 18–month period targets
42	$t_2 + 6$	Install rotating whirl control (as required in GG)
48	$t_2 + 12$	Measure patch effects and demonstrate that they are not relevant; improve sensitivity to effect from Sun @ 24 h by Phase Sensitive Detection in preparation for analysis of space data
54	$t_2 + 18 = t_3$	Optimize test masses different composition, manufacture test masses, measure their quadrupole moments and confirm requirements
		Fourth 18–month period targets
60	$t_3 + 6$	Manufacture suspensions required for GG in space, measure their elastic constants and quality factors and confirm fulfilment GG requirements
66	$t_3 + 12$	Demonstrate on bench laser gauge read out noise to $r_{laserRO} \simeq 10^{-12}\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ @ $1 \div 2$ Hz
72	$t_3 + 18 = t_4$	Test PZTs and inchworms to demonstrate feasibility of balancing in space

Table 3: GGonGround Roadmap

6 Budget Tables

Budget Table (in €) for the Corresponding Principal Investigator Anna M. Nobili						
	Cost Category	Months 1–18	Months 19–36	Months 37–54	Months 55–72	Total
Direct Costs	Personnel:					
	PI	44000	44000	36000	36000	160000
	Senior Staff (1)	118500	118500	118500	118500	474000
	Post Docs (1)	67500	67500	67500	67500	270000
	Students (PhD, 2)	60000	60000	60000	60000	240000
	Other (Dr. R. Pegna)	118500	118500	118500	118500	474000
	Other (1 mech. engineer)	67500	67500	67500	67500	270000
	Other (Dr. G. Catastini)			66000	66000	132000
	Other (Dr. D.M. Lucchesi)	13500	13500	13500	13500	54000
	Other (1 Junior Staff)	105000	105000	105000	105000	420000
	Other (1 admin. assistant)	53550	53500	53550	53550	214200
	Total Personnel:					**2708200**
	Other Direct Costs:					
	Equipement (eligible fraction only)	235000	275000	275000	275000	1060000
	Consumables	25000	25000	25000	25000	100000
	Travel	92700	92700	100950	100950	387300
	Publications, dissemination etc..	49500	49500	49500	49500	198000
	Other (removal and lab set up)	50000				50000
	Total Other Direct Costs	452200	442200	450450	450450	**1795300**
	Total Direct Costs	1100250	1090250	1156500	1156500	**4503500**
Indirect Costs	Max 20% of Direct Costs	220050	218050	231300	23130	900700
Subcontracting Costs (auditing)	(No Overheads)	10000	10000	10000	10000	40000
Total Costs of Project:	(By Year and Total)	1330300	1318300	1397800	1397800	**5444200**
Requested Grant:	(By Year and Total)	1330300	1318300	1397800	1397800	**5444200**

Working time the PI **A.M. Nobili** dedicates to the project over the period of the grant						
		Months 1–18	Months 19–36	Months 37–54	Months 55–72	Average
		73.3%	**73.3%**	**60%**	**60%**	**67%**

Budget Table (in €) for the Principal Investigator Guido Zavattini						
	Cost Category	Months 1–18	Months 19–36	Months 37–54	Months 55–72	Total
Direct Costs	Personnel:					
	PI	24000	36000	36000	36000	132000
	Senior Staff (1)	118500	118500	118500	118500	474000
	Post Docs (1)	67500	67500	67500	67500	270000
	Students (PhD, 1)	30000	30000	30000	30000	120000
	Other (Dr. Mike Shao)	37500	37500	37500	37500	150000
	Other (2 Junior Staff)	210000	210000	210000	210000	840000
	Total Personnel:	487500	499500	499500	499500	**1986000**
	Other Direct Costs:					
	Equipement (eligible fraction only)	210000	230000	200000	200000	840000
	Consumables	25000	25000	25000	25000	100000
	Travel	102000	125000	92000	92000	411000
	Publications, dissemination etc	30000	30000	30000	30000	120000
	Other					
	Total Other Direct Costs	367000	410000	347000	347000	**1471000**
	Total Direct Costs	854500	909500	846500	846500	**3457000**
Indirect Costs	Max 20% of Direct Costs	170900	181900	169300	169300	691400
Subcontracting Costs	(No Overheads)					
Total Costs of Project:	(By Year and Total)	1025400	1091400	1015800	1015800	**4148400**
Requested Grant:	(By Year and Total)	1025400	1091400	1015800	1015800	**4148400**

Working time the PI **G. Zavattini** dedicates to the project over the period of the grant						
		Months 1–18	Months 19–36	Months 37–54	Months 55–72	Average
		40%	**60%**	**60%**	**60%**	**50%**

Summary Table for the Entitre Budget (in €)						
	Cost Category	Months 1–18	Months 19–36	Months 37–54	Months 55–72	Total
Direct Costs	Personnel:					
	PI	68000	80000	72000	72000	292000
	Senior Staff	237000	237000	237000	237000	948000
	Post Docs	135000	135000	135000	135000	540000
	Students	90000	90000	90000	90000	360000
	Other	605550	605550	671550	671550	2554200
	Total Personnel:	1135550	1147550	1205550	1205550	**4694200**
	Other Direct Costs:					
	Equipement	445000	505000	475000	475000	1900000
	Consumables	50000	50000	50000	50000	200000
	Travel	194700	217700	192950	192950	798300
	Publications, dissemination etc	79500	79500	79500	79500	318000
	Other	50000				50000
	Total Other Direct Costs	819200	852200	797450	797450	**3266300**
	Total Direct Costs	1954750	1999750	2003000	2003000	**7960500**
Indirect Costs	Max 20% of Direct Costs	390950	399950	400600	400600	1592100
Subcontracting Costs (auditing)	(No Overheads)	10000	10000	10000	10000	40000
Total Costs of Project:	(By Year and Total)	2355700	2409700	2413600	2413600	**9592600**
Requested Grant:	(By Year and Total)	2355700	2409700	2413600	2413600	**9592600**