POSSIBLE SYNERGIES BETWEEN THE "SPACE WEATHER PILOT PROJECT" AND THE "GMES" PROGRAMME

In November 2001 the ESA Ministerial Council approved a new 5 year programme dedicated to GMES (Global Monitoring for Environment and Security), called the Earth Watch GMES Service element (GSE for short). This programme is the first one dedicated to the ESA/EU GMES initiative. It is a program which will deliver policy-relevant services to end-users and vital information on environmental and security, primarily but not exclusively on the basis of Earth observation through spatial instruments. A preliminary list of GMES potential priority areas has been established jointly by ESA and EC in June 2001 (*Table 1*). The ITT concerning this first step in the ESA involvement in GMES (which is to be led by the Earth Observation Programme directorate) has been issued in September 2002 (Ref.: AO/1-4302/02/I-IW)[1]. The result of this "consolidation action" (strand 1 of GSE) shall be delivered at the end of 2003.

Two and a half year before (April 2000) the TOS/EMA division of ESA had started a preliminary evaluation of the potential benefit and feasibility of a programme to monitor (and possibly predict) the Sun-Earth environment parameters in order to prevent or mitigate the deleterious effects of the solar activity: the ESA "Space Weather Programme" (SpWP). This evaluation was done through two contracts and under the continuous supervision of a "Space Weather Working Team", consisting mainly but not exclusively of European scientists and industrials. Finally a "pilot project" (SpWPP) was defined for three years (2002-2003). An AO concerning this project was issued in July 2002 (Ref.: AO/1-4246/02/NL/LvH). In this tender action, ESA proposes to fund 15 sub-projects among anticipated candidate user domains (*Table 2*) on a share-funding basis. Two other tender actions are planned: one to support the service development and a second one to perform the quantitative benefits assessment of the services.

The purpose of the present analysis is to evaluate - from a thematic point of view –to what extent the SpWPP could be integrated in the GSE initiative. After a brief discussion of the similarities and differences (in terms of methodology, structures, etc.) that exist between the two programmes, we will suggest some routes that could be explored in order to take the greater benefit of the European assets and expertise which were so successfully scrutinized during the two years of cooperation between ESTEC/TOS/EMA, the SWWT and the two contractors.

1. Similarities and differences between the two approaches

Table3 summarizes the characteristics of both projects. Apart from the fact that there is a large difference between their budget and that the thematic of the bids is more clearly focused in SpWPP than in GSE, both ITT's are aimed at satisfying user needs with important social and economical return. They also both demand - at different levels of definition – that the bidders demonstrate their ability to organize operational and sustainable

[1] Note that this ITT is very general and does not make specific reference to the "potential priority list" given in table 1. The ESA / EU document "SEC (2001)" is just mentioned as a reference document.

services in support for environment and security policies (SpWPP being restricted to risks associated with the Sun- Earth environment). They both want to promote the use of existing EO instruments (spatial or ground based) and to initiate the development of new ones.

But there is a large difference between the communities toward which the ITT's are addressed. In the GSE/ITT the "end-users" are governmental agencies, public or private organizations that have a legal obligation or public duty to monitor and report on environmental issues. In the SpWPP terminology an "end-user" is an organization, public or private which will make use of the offered service, if possible by paying (electric or aircraft companies f.i.). One sees that there will be difficulties in trying to merge the two approaches.

2. Some topics that are relevant to both ITT's

Since the proposals that have been submitted in answer to the SpW Pilot Project ITT are not in the public domain, it is not possible to select one proposal or another and say "this one or that one would fit well within the GSE priority theme X or Y". However almost all the deleterious effects hat have been analysed by the two contractors and the Space Weather Working Team result in the loss of the 100% availability of the GSE instruments that are needed to fulfill the objectives listed in *Table 1*. Therefore it is easy to list those SpW effects which are the most important in that respect and whose monitoring could be considered as essential to the success of the GSE programme. The way in which the symbiosis between the two approaches could be organized at the decision level is outside the scope of the present analysis.

The solar influences that are relevant to our subject can be divided into three main topics:

1. The solar UV radiation and its effects on the Earth's magnetosphere, thermosphere, ionosphere, the ozone layer and finally the health of human beings on the ground (especially those living at high latitudes or altitudes).
2. The geomagnetic perturbations that are induced by solar flares, CME's (Coronal Mass Ejections) or other solar wind disturbances, with their consequences on spacecraft anomalies, ionospheric transmission properties, Geomagnetic Induced Earth currents (GIC's) or pipeline corrosion.
3. The energetic particle radiation whose flux is modified by solar eruptions or by solar wind properties and which affects spacecraft operations, ionospheric transmission and the health of aircrew members or astronauts.

In *Table 4* a matrix is presented in which each of these three main solar influences is related to a region of the Earth environment, to a technological device or to a human health problem, as well as to specific SpW Pilot Project domains or to GMES priority themes. Justification of this matrix follows, by ordering the demonstration first by the physical parameter, second by the region or the effect which is concerned.

2.1 UV radiation

Besides of the variation of the sunspot number the increase of the UV flux is the primary manifestation of an increased solar activity[2]. Whereas the fluctuation of the solar

[2] Its variation is closely associated with the variation of the solar flux at 10. 7 cm wavelength (F 10.7) which is often used as a proxy.

radiation in the visible (both cyclic and sporadic) is of the order of a few tenth's of a percent, in the UV range these fluctuations may reach a few percents, the fluctuation being more important at the shortest wavelengths.

2.1.1 Atmospheric drag

These wavelengths (~ 200 nm) are absorbed in the high altitude atmosphere (~ 300-1000 km) and the solar cycle variation of their flux is at the origin of the solar cycle variation of the thermospheric temperature, density and composition (mainly O_2). But the sporadic changes of this UV flux induce sporadic changes in these thermospheric parameters, with important incidence on **the atmospheric drag** exerted on orbiting spacecraft. The correct prediction of the localization of Earth Observing satellites is an important operational aspect of the usefulness of theses satellites. Therefore the monitoring an the forecasting of the solar UV flux at these wavelengths is fundamental for **Global Atmospheric Modelling** (**item E**) and the total availability of **Risk Management Systems** (**item G**)[3].

Another consequence of the atmospheric heating is the somehow unpredictable **date or place** on the Earth where a spacecraft will reenter the atmosphere and eventually hit the ground. This is illustrated for instance by the error of 3 months in the prediction of **the life time** of the European satellite MAGSAT because of an error in the prediction (4 months in advance) of the sunspot number[4]. More important for security is the **predicted place of reentry of large spacecraft**, especially when they contain nuclear reactors. For example SKYLAB (a US spacecraft of 75 tons) which ended its life over Australia in July 1979, or SALYUT 7 (a Russian spacecraft of 40 tons) which ended its life over South America in February 1991[5]. But these problems are more of concern to space agencies and to scientific institutions that have to improve their models and their prediction capabilities.

It must be noted that the atmospheric drag fluctuations are associated not only with variations in the UV flux, but also <u>with the occurrence of geomagnetic storms</u> (see section 2.2). The respective role of these two processes is not yet completely clarified. This has important consequences with respect to the establishment of a reliable forecasting system since the UV flux and the geomagnetic activity have not the same predicting level of confidence <u>nor the same warning time delay</u>.

2.1.2 Ionospheric perturbations

In association with X rays the UV light is also the origin of the ionisation in the high altitude atmosphere (~ 100-600 km). During solar events the ground-to-ground telecommunications (trough HF links) are perturbed. The satellite-to-ground transmissions (at GHz frequencies) which are used for wide band telecommunications, localization or navigation systems are also modified, either in their <u>transit tim</u>e, with **subsequent errors in positioning**, or through <u>scintillation effects</u> which induce a **loss of signals**.

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[3] At these wavelengths the UV flux can only be measured from space. Hence the interest of a full SpW programme that may continue the SpW Pilot Project.

[4] *EOS*, **61**, 475, 1980.

[5] H. Klinkerad, *ESA/SP*, **392**, 287-298, 1996.

These perturbations have a world wide distribution but they occur more often in the high latitudes or polar regions[6], though the UV radiation enhancement is not the principal cause of these perturbations at these latitudes (see sections 2.2 and 2.3).

Modern techniques to determine the total ionospheric electron content (TEC) at different positions are now available. Changes in the travel time of global positioning signals such as those which will be transmitted by GALILEO can therefore be computed in almost real time. Such techniques will be useful for the accuracy of the navigation and positioning services (items 6 and 7 of the SpW PP), which are a must for the "*stability of man made structures*" (**item G** of GSE), and the *"European Spatial Data Infrastructure"* (**item I**).

2.1.3 The ozone layer

Monitoring the **atmospheric ozone content** is not a primary objective of the SpW Pilot Project. But a detailed survey of the UV flux at different wavelengths may give, as a by-product, useful information of the production rate of ozone molecules at different altitudes. This is one of the concerns of the GSE programme (**item E**). The diminution of the stratospheric ozone content is the reason why UV B (280-320 nm) can reach the ground in larger quantities (see below).

2.1.4 Human health

The effects that these UVB have on the proliferation of **skin cancers** (**melanomes**) on human beings is well known. There is a clear correlation between their yearly number and the solar cycle. The fact that their annual number has dramatically increased during the past 50 years is mainly related to the modern way of life of the western world inhabitants, but the continuous decrease of the ozone protection (**the ozone hole**) in the Northern as well as in the Southern countries is also a subject of concern.

UV monitoring at ground level is an activity which is already supported by a large number of European governments. But in order to have a long term view about the evolution of this flux it may be good to follow the variation of the UV flux at the top of the atmosphere. Such a monitoring would easily be part of **item E** of the GMES programme.

2.1.5 Biological ecosystems

Because of is strength of penetration UV radiation is able to penetrate the ocean layers and to play a role in the **production of plankton**. The relative efficiency of photosynthesis at visible and UV wavelengths is not yet firmly established. But if one take into account the importance of plankton production in **the capacity of oceans to absorb atmospheric CO_2** one sees the indirect interest that the knowledge of the UV flux and of its variation may have on the problem of climatic change. Clearly such processes are not directly relevant to the SpW PP and they can only be marginally considered for **items D and E** of GMES.

2.2 Geomagnetic storms

[6] Where most of the transcontinental air traffic take place, for which it is mandatory to maintain reliable telecommunications. .

Contrary to solar UV perturbations which reach the Earth almost instantaneously (within 8 minutes) geomagnetic storms occur at different times after their causative phenomena (30 mn for storms generated by CME's if they propagate directly to the Earth, to 2 to 3 days for storms generated by solar wind enhancements). In the second case a **forecast of the order of one hour in advance** is possible if one can detect the arrival of the perturbation at the first Lagrangian point (L 1 situated at ~ 1. 5 x 10^6 km from the Earth in the Earth-Sun direction) is possible[7].

These magnetic perturbations which may last for 2 or 3 days and whose intensity is grossly defined by a 3 hour index (Kp or Aa) are mainly the symptom of an **injection of medium energy particles** (10 keV to a few MeV) originating directly from the solar wind or energized in the tail of the magnetosphere. The consequences of these injections (those that are related with problems of environment and security) are described below.

2.2.1 Spacecraft anomalies

During geomagnetic storms energetic particles penetrate quickly to geocentric distances as low as 4 R_e producing what is called **the ring current**. Geostationary or eccentric satellites are thus imbedded in an energetic plasma which induce **electric discharges** in their outer components with concomitant **dysfunctions or loss of data**. During intense storms "**killer electrons**" (E > 2 MeV) are injected which may produce **irreversible deficiencies** and sometimes the **loss** (total or partial) **of the spacecraft**. In many cases the operability of the spacecraft is reduced for long periods (a few hours) with an **important economic loss**[8].

Having information in advance about the probable occurrence of such phenomena may help in putting the spacecraft in a safety mode, thus avoiding disastrous effects. Besides of their economic and societal importance, satellites will play a more and more important role in **risk management**; their **operational capacities** must be permanent. This is of concern to **GMES item G** (operational support of risk assessment and stability of man made structures[9]).

2.2.2 Auroral zone effects

During geomagnetic storms perturbations of smaller duration (a few hours) often occur (the substorms) during which charged particles of lesser energy (10-100 keV) are precipitated in the auroral zones where they induce **visible auroras**[10] and **ionospheric perturbations** whose consequences have been described in section 2.1.2.

2.2.3 Earth induced currents

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[7] Hence the interest of having a spacecraft permanently situated around this position.

[8] See C. Dyer and D. Rogers, *ESA/WPP*, **155**, 17-27, 1999, for a review.

[9] Spacecraft (principally Earth Observation but also Telecommunication and Navigation satellites) are "*man made structures*" which must receive "*operational support*" such as the one which could be provided by a Space Weather Programme.

[10] Predicting the occurrence of polar auroras has an incidence on tourism (item 15 of the SpWPP). Operational services are already exist that are produced by some European laboratories, but they cannot be considered as relevant to the GMES programme.

During these events the **auroral zone and the polar cap** are subject to changes in the ionospheric electric fields. Strong currents circulate at ionospheric levels which induce currents of similar amplitudes in the Earth below. These **geomagnetically induced currents** (GIC's) have three consequences:

- they circulate in the in the neutral of the **electric power lines network** (which by conception is not supposed to transfer large currents), inducing disruptions in transformers and – in extreme cases – loss of the whole electric network for few hours[11].
- they circulate in **pipelines**, inducing increased corrosion.
- they prevent making reliable **prospecting** operations (**item 2 of the SpW PP**).

Apart from the corrosion of pipelines which can be mitigated by the injection of counter currents, the two other effects have important economic consequences: new electric power generators must be put into operations; prospecting campaigns must be postponed.

Warning about geomagnetic storms (a technique which starts to be more and more reliable provided one continue to benefit from the existence of satellites at L 1) is a **must** for protecting important man made structures (**item G of the GMES** programme) or economic activity.

2.2.4 Health problems

Some studies, principally made in the former Soviet Union, seem to show a positive correlation between the daily number of **heart attacks** or **brain strokes** in large cities and the occurrence of severe geomagnetic disturbances[12].

The mechanisms which could explain such correlations are poorly known and further studies are needed. But if these effects were confirmed it is clear that a warning of the possible occurrence of these magnetic perturbations would be of **great benefit for the society**. This could be taken in charge by Met Offices[13] in each country or centralized at the European level.

2.3 Energetic particles

One must distinguish between **Galactic Cosmic Rays** (GCR's, E > 1 GeV), **Solar Cosmic Rays** (SCR's, E ~ 10-100 MeV) and other energetic particles that are accelerated by intra-solar wind processes or by solar wind-magnetosphere interactions.

- The flux of the GCR's reaching the Earth **decreases** when the solar activity increases, because the (week) magnetic field which is imbedded in the solar wind diffuse these particles into the heliosphere.
- On the contrary the flux of cosmic rays of solar origin **increases** during solar activity and is the cause of many disturbances in the Earth environment at all altitudes. Intense fluxes of these particles are observed during **CME's**.

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[11] The most famous example of such a consequence is the March 13, 1989 current disruption in Quebec which lasted for 9 hours, involved 6 millions of people and has cost 13 millions of dollars to Hydroquebec.

[12] Similar correlations seem to exist with vehicular traffic accidents (J.G. Roederer, *Space Medicine and Medical Engineering*, **9**, 8-16, 1996)

[13] Similarly to pollution alerts that are notified to asthmatic people when the concentration of ozone in the air at ground level exceeds a certain threshold.

- Particles of smaller energy (< 10 MeV) are produced by different mechanisms, most of them being linked with geomagnetic storms.

2.3.1 Earth magnetosphere and spacecraft

Cosmic rays are at the origin of the **radiation belts** through the CRAND process (Cosmic Ray Albedo Neutron Decay, a nuclear interaction between CR's and the atmosphere and the subsequent decay of the neutrons that are produced during this interaction). During intense CR events the belts are filled at nearer and nearer geocentric distances and their "**horns**" (near 40^o geomagnetic latitude) penetrate deep into the exosphere, down to altitudes of the order of ~ 400 km. These altitudes and latitudes are the ones which are crossed by many **transfer orbits** during which one cannot afford any electronic dysfunction.
The **International Space Station** spends also a non negligible time at this latitude and altitude. The **South Atlantic Anomaly** where the horns of the inner radiation belt penetrate already at lower altitudes (~ 200-300 km) is also subject to increased fluxes of energetic particles; this region is crossed by many low orbiting spacecraft and during transfer orbits to higher altitudes. The deleterious effects that are produced by these very energetic particles are much more dangerous than the ones that have been reported in section 2.2.1.

One could argue that the protection of spacecraft operations and launches is under the unique responsibility of the space agencies. But this is only partly true since our society and its security are more and more depending on spacecraft technology. In some respect a comprehensive GSE programme should include part of this space weather aspect (**item G**).

2.3.2 Ionospheric effects

Because of the shape of the Earth's magnetic field the polar regions are more accessible to solar particles above 1 MeV which can penetrate down to ionospheric altitudes in the D layer an produce strong absorption at HF frequencies. Such events are called **Polar Cap Absorption** events (PCA's). They may last a few days and prevent any HF communication at these latitudes (~ 70^o) <u>putting in danger the security of small commercial expeditions on the ground, on the air or on the oceans.</u>

2.3.3 Stratosphere (ozone)

The role of CR's in the **destruction of ozone,** with its associated consequences on the health of human beings (see section 2.1.4) through the final production of NO_x molecules at altitudes of ~ 20-30 km is recognized since long, though their relative importance with respect to the role which is plaid by CFC's or HCFC's is not yet well established. But the fluorocarbons have a permanent effect whereas the cosmic rays occur only sporadically so that this does not concern really the GMES programme.

2.3.4 Troposphere

Though they are subject to controversy recent studies seem to demonstrate that that there is a positive correlation between the cosmic ray flux (in that case mainly the GCR's) and the cloudiness at tropospheric levels. The mechanism which is suggested is that CR's could facilitate the **nucleation of droplets** inside the clouds.

Cosmic rays are also involved in the modification of the **Global Electric Circuit** which exists between the ground and the ionosphere through ionisation which they induce at low altitude (<10-15 km), thus having an influence on **thunderstorm activity.** But such processes are not of concern to the GSE programme.

2.3.5 Air crew and astronauts

Following the ECC directive 96/29/Euratom (May 1996) the European Union has issued in May 2000 (!) a directive which regulates the **maximum dose of radiation** that European **air crew members** (or air crew of European companies?) should receive during their long-haul flights at high altitudes which cosmic rays are able to reach during perturbed conditions[14].

A lot of experimental studies have been made by scientists of **radiation protection institutes and air line companies**. The measurement techniques have been tested but it is not possible to equip each air crew member with dosimeters. Reliable models of the total dose that is received during a given flight are now available, which are based upon ground measurement of cosmic rays via **neutron monitors**[15].

Fortunately it appears that during long-haul flights from Europe to California or to Japan (as well as for flights form Europe to South America which pass through the South Atlantic Anomaly) the maximum integrated dose has never exceeded ~ 300 mSv even during the March 1989 GLE (Ground Level Enhancement of CR's). But with the tendency toward **higher altitude flights** in the coming years, a more coordinated system for the protection of air crew members and frequent air passengers should be implemented[16]. This is clearly of concern to **GMES items G and I**.

The problem of **astronauts** who flight permanently at high altitudes is even more crucial. They must be warned immediately when a CR event is forecast, especially during **Extra Vehicular Activities** (EVA's). The crew of **interplanetary flights**, which are envisaged for the years ~ 2020 are put in even more dangerous conditions. It has been statistically evaluated that during solar minimum GCR's would induce doses exceeding the annual limit recommended by the EC if the crew were protected by a shield of 5 cm of aluminum (remember that a flight to Mars would last, with the present techniques, of the order of two years back and forth). This does not include effects produced by SCR events which could lead to **lethal doses**, as the one that could have killed the American astronauts if they had been on the Moon in October 1989.

However such risks **are to be taken care of by space agencies** which are responsible for these flights (ISS and interplanetary missions). **They do not concern** the GMES Programme.

[14] The effective dose should not be higher than 100 milli Sievert (100 mSv) over 5 years with a maximum of 50 mSv during a given year. Specific rules are issued for pregnant aircrew members: the fetus should not be subject to more than 1 mSv up to the end of the pregnancy.

[15] For instance the Sievert system (http://www.dgac.org) has been established under the auspices of Air France, CNES and the French Institute for Nuclear Protection.

[16] The more and more sophisticated electronic circuits which invade avionic systems will be subject to enhanced perturbations during these higher altitude flights, a problem which is probably not of direct concern to GMES but which should be considered as a valuable topic for FP 6 (see Table 6, item 1.1.4: Aeronautics and Space).

2.3.6 Avionics

In a reasonable future aircraft will fly at **higher altitudes.** Their **electronics** will be more sophisticated and **more sensitive to radiations**. Consequently they will be the subject of more SEU (**Sudden Event Upsets**) during CR events (especially for those flights that cross the polar regions). Such effects could put in danger the aircraft, their crew and passengers.

By monitoring (and better predicting) the occurrence of such CR flux enhancements, it will be possible to direct the flights toward lower altitudes or latitudes, thus increasing the safety of materials and personnel. Clearly this aspect of protection of assets and people is of concern to **GMES items G and I**, in close coordination with aircraft industry and aircraft companies.

2.4 Other components

There are other space weather effects or phenomena which are not addressed in details in this analysis (electromagnetic radiation, micro-particles from natural planetary environment or issued from spacecraft debris) because they are more marginally relevant to GSE in terms of impacts. However these effects or phenomena may become critical as occupation of space and sensitivity of systems increase.

3. A third Partnership

Another initiative, from the EC, is offering interesting perspectives for the development of space weather activities in Europe. In order to finalizing its FP 6 (Framework Programme number 6) for the next four years (2003-2006) the European Commission has launched an ITT to stimulate **Expressions of Interest** (EoI's) among the scientific community, public institutions and private enterprises. The AO was issued the 20th of March. Preliminary answers were due the 7th of June and the deadline (for those who will be allowed to submit) is in November. One may submit for a "Network of Excellence" (NoE) or an "Integrated Project" (IP). In both cases industrial contributors must play a non negligible role. SWWT members have submitted Expressions of Interest to this ITT (*Table 5*).

The EC has defined 12 priority thematic areas (*Table 6*) among which 4 seem relevant to the Space Weather Pilot Project. But the representatives of the EC are rather strict as far as the interpretation of these priority areas is concerned. Space weather activity in itself is not, up to now, considered as a key priority in any of the specific "space", "aeronautics", "global change" or "radiation protection" domains. It is well understood however that it potentially represents a cross-thematic activity to all of these domains, for which the complexity of the management of the research laboratories and operational resources would justify an involvement in FP 6.

Knowing the importance that a **100% availability of Earth Observation Satellites or Telecommunication and Navigation systems** have on the assessment or management of natural risks and disasters, it is clear that a coordinated monitoring and forecasting of the deleterious effects that solar activity or Sun-Earth relationships may have on those satellites or systems is necessary and should appear in the European Fp6 !

Space weather is already considered at another level by the EC. A new programme has been accepted in the COST initiative, **COST 724**: *Developing the scientific basis for monitoring, modelling and predicting Space Weather*. There also exists an already running COST initiative related to the ionospheric effects of space weather on telecommunication and navigation: **COST 271**. This will allow interested European scientists to meet together and to continue defining precise coordinated research projects on the subject. **Synergies between GSE, FP 6 and COST will be beneficial to all these activities.**

4.Conclusion

By choosing a physical description of the mechanisms that are at the origin of space weather (with both its quiet conditions and its violent explosions) one was able to specify in more general terms those effects that endanger the reliable monitoring of the Earth environment and its management.

Without implementing a full-fledged space weather programme by the use of dedicated spacecraft it is possible to embark small equipments on already programmed satellites (for science or applications). Many measurements that are required for space weather effects monitoring and forecasting are already considered as current Earth observation payloads. These include the measurement of geomagnetic field (f.i. the Danish programme Oerstedt and the ESA project SWARN), UV radiation, thermospheric wind and density. Others like measurements of space or solar radiations could easily be accommodated on Earth observation satellites. In that respect it is interesting to note that the NPOESS and METOP polar sun-synchronised spacecraft, which will constitute an operational joint US-European constellation for weather monitoring, will embark space environment sensors which will provide data on magnetic fields, energetic particles, TEC, thermospheric winds, etc[17].

Though not identical to, the Space Weather thematic is relevant to GMES's, in term of both the measurements and the service provision requirements. Last but not least the establishment of a programme about SECURITY must take into account the SECURITY, RELIABILITY and INDEPENDENCY of its tools…

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Roger Gendrin , 27/ 11 / 02

[17] E-mail from A. Hilgers dated March 20, 2002.