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# SYSTEMS CONSIDERATIONS OF WEATHER MODIFICATION EXPERIMENTS USING HIGH POWER ELECTROMAGNETIC RADIATON

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## ABSTRACT

The average energy turnover in storm systems can range from 7 x $10^9$ watts in small thunderstorms to 7 x $10^{14}$ watts in a hurricane. In the mid 1980's, antennas producing up to $10^{12}$ watts using natural gas on the North Slope of Alaska were studied by ARCO and the U.S. Department of Defense for military applications in the ionosphere. Because of the similarity between the proposed antenna power and the energy turnover of some typical storm systems, applications for weather modification in the troposphere were proposed. It was also suggested that the large ARCO antennas could be used for molecular modification of the atmosphere.

This paper reviews the physics and technology basis of the patents that resulted from the ARCO work. Subsequent studies by Eastlund Scientific Enterprises Corporation have focused on applications of antenna systems in the range of 200 to 10000 megawatts, which can be powered by a variety of conventional means or by solar power satellite systems. Mitigation of tornadogenesis in thunderstorms has been a subject of investigation. It is hypothesized that rain-cooled downdrafts are responsible for the formation of tornadoes. A system for targeting and tracking these downdraft regions and heating them with focused beams of electromagnetic radiation, in the hope of interfering with tornado development, will be described. Storm-scale weather prediction simulation codes are used to determine the potential effectiveness of the heating events. Use of the WSR-88D Doppler radar network as an aid to targeting and steering the focused beam on these downdraft regions is described.

Other systems, in which feasible ground and satellite based antennas would deliver heating power to specific regions of weather patterns in order to minimize the development of dangerous weather systems will be discussed. The paper will also treat the need for careful impact assessments and consideration of socio-economic/political and legal/regulatory issues. Finally, experiments utilizing existing antenna systems are proposed to investigate the scaling and beam control necessary for such applications.

## 1. INTRODUCTION

### 1.1 Background

The reduction of severe weather impact by dissipation or diversion of associated weather systems can be envisaged, via concepts which utilize various technological options, such as airborne cloud seeding, or with selective tropospheric heating from beams of electromagnetic radiation emitted from satellite and/or ground based antenna.

System engineering issues include:

- Weather Modeling and Storm Measurement

  Numerical weather modeling must be sufficiently well developed to provide storm-scale weather prediction in real time based on input from a variety of sensors.

- Electromagnetic Wave Generation

  Electromagnetic wave generators must be available at appropriate cost in the appropriate wavelength. (i.e. RF, microwave, millimeter, infrared, optical or uv.)

- Antenna Transmission

  Antenna for severe weather applications will need accurate phase control over large apertures, high power, and be integrateable with the design of the power generation methods.

- Propagation

  Propagation of the beam from the antenna to the appropriate fine structure is required.

- Weather Modification

  Heating of appropriate features of a storm must be shown to decrease the severity of the storm.

- Results Assessment

  Diagnostics of the effectiveness of the results of the modification will be crucial to practical severe weather control.

Weather modification which exceeds the scale of conventional cloud seeding (tested in the 1940s through the 1970s) reaches quickly energy and scale dimensions which are well beyond the current technical feasibility of space systems. The average energy turnover in storm systems can range from 7 x $10^9$ W in small thunderstorms to 7 x $10^{14}$ W in hurricanes and typhoons (Ref. 1). In the mid 1980s, the author studied antennas producing up to $10^{12}$ W using natural gas on the North Slope of Alaska for the US Department of Defense for military applications in the ionosphere. (Ref. 2-4,7-8) Because of the similarity between the proposed antenna power and the energy turnover of some typical storm systems, applications for weather modification in the troposphere were proposed. Other systems, in which feasible ground and satellite based antennas would deliver heating power to specific regions of weather patterns in order to minimize the development of dangerous weather systems, can also be envisaged.

It has to be born in mind that Earth ecosystems exhibit many forms of instability, including strong non-linear behavior (hysterisis) and dynamic chaos. The development of long range weather and climate forecast capabilities over the last decades has shown that, apart from an immense increase in data volume and quality, computer power and process understanding, the limits of predictability are near and cannot be overcome by technology yet. Future improvements of weather forecasting are likely to happen because of improved instrumentation, better data coverage, and advanced algorithms from Earth observation. Additionally, near real-time data access, and data assimilation into models of temperature, wind, humidity profiles, rainfall rates, cloud liquid water, surface wind, energy exchange (latent, sensible) at the surface are expected to improve forecasting. Climate modeling will improve by increasing the model resolution, model nesting, improved process parameterization, better coupling with ocean models, better assessment of geosphere-biosphere-atmosphere interactions.

Severe storm systems, such as mesocyclones that spawn tornadoes in North America have been numerically modeled successfully. (Ref. 5-6,9-10) Numerical models can describe the development of mesocyclones and exhibit tornado like rotation. Most importantly, the results of these calculations, in the case of severe weather are reproducible on time scales over which attempts could be made to modify the weather system. (Ref. 11) Thus, while climate modeling may never be able to make long range forecasts with reliability, numerical models of severe storms may already be sufficiently well developed to allow proper risk assessment of artificial perturbations of small mesocyclones.

The goal of implementing operational geoengineering by space systems overcoming all scientific, political, legal, and financial problems within the next 30 years may well prove unlikely. However, there is a definite need to look more precisely into the possible options, and, as a first step, this study shall define more in detail a number of those options.

## 2. SEVERE WEATHER PHENOMENA

Severe weather in the form of tornadoes and hurricanes (cyclones) are responsible for hundreds of deaths and property damage in the billions of dollars each year in the United States alone. Other severe weather such as typhoones in the Pacific, and droughts and floods similarly wreak havoc each year. There is some thought that the global warming phenomena could further intensify these phenomena.

A worldwide effort to better forecast and measure the behavior of these weather phenomena is well underway. However, as stated by Jenkins (Ref. 12), "Research to understand Earth system processes is critical, but it falls short of providing ways of mitigating the effects of environmental change. Geoengineering options and alternatives to interactively manage change need to be developed."

With the exception of some cloud seeding experiments (Ref. 13) and suggestions in the previously discussed patents (Refs. 2-4), little serious work has been considered in terms of mitigating the effect of severe storms.

The sheer size and energy of severe weather systems is one of the daunting aspects discouraging pursuit of weather mitigation concepts.

### 2.1 Scales of Atmospheric Phenomena

Figure 1 illustrates the wide range of windspeeds and scalelengths (wavelength) of weather phenomena. (Ref 14) Still another method of classification is via the average energy turnover of storm systems.

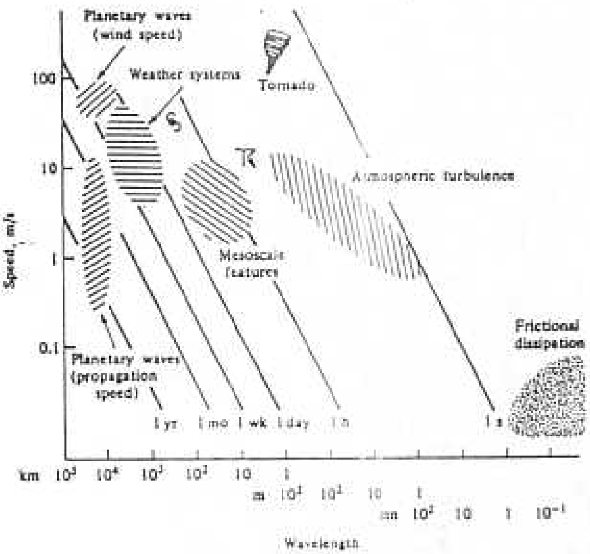


FIGURE 1

*Scales of atmospheric phenomena. For many of these phenomena, it is possible to choose different length or speed scales, thus giving quite different time scales.*

Table 1 is taken from a recent Air Force Geophysics Laboratory paper (Ref. 1) on weather modification possibilities. The energy turnover is based on the rainfall rate. Note that the energy turnover ranges from $7 \times 10^9$ watts for a small thunderstorm to $7 \times 10^{14}$ watts for a hurricane.

TABLE 1

| | |
|---|---|
| SMALL THUNDERSTORM | $7 \times 10^9$ WATTS |
| LARGE THUNDERSTORM | $7 \times 10^{11}$ WATTS |
| MAJOR STORM SYSTEM | $7 \times 10^{13}$ WATTS |
| HURRICANE | $7 \times 10^{14}$ WATTS |

2.2 Dynamic Meteorology

The theoretical study of the atmospheric motion of weather phenomena is known as "Dynamic Meteorology." (Ref. 14) Dynamic meteorology involves the understanding of the phenomena and provides a basis for prediction of weather.

Numerical modeling of weather has resulted in development of codes that can start from initial conditions of temperature nonuniformity and measured wind directions and then compute severe weather phenomena that can reproduce features of severe storms. The Advanced Regional Prediction System (ARPS) code at the Center for Analysis and Prediction of Storms (CAPS) center at the University of Oklahoma is one such code. (Ref. 15) The ARPS code is used in this systems analysis to determine the effect of electromagnetic wave heating of mesocyclones (thunderstorms) and to estimate the energy requirements for tornado mitigation concepts. The ARPS numerical model is a three dimensional, nonhydrostatic, compressible model in generalized terrain following coordinates, and is run on a CrayC90 at CAPS.

The governing equations of the atmospheric model component of ARPS include conservation equations for momentum, heat (potential temperature), mass(pressure), water substance (water vapor, liquid and ice) subgrid scale turbulent kinetic energy and the equation of state of moist air.

Assessment of the predictability of storm-scale flows has been one of the areas of research at CAPS. In these numerical studies, supercells (intense storm prediction) showed mild sensitivity to changes in the initiating disturbances. In contrast, weaker systems varied considerably with identical changes in the initial conditions. (Ref. 11) Thus, when the severe weather features appear in the calculations, they are reproducible, giving us confidence that they may be sufficiently well enough developed to be used as a predictive tool to assess the probable effects of weather modification attempts.

3.0 NORTH SLOPE GAS CONCEPTS-IONOSPHERIC MODIFICATION

Severe weather in the troposphere is the primary concern of this paper. However, the ionosphere and the mesosphere exhibit strong resonances with electromagnetic waves and have been the subject of considerable modification research. Figure 2 illustrates the altitudes of these regions compared to the troposphere and the stratosphere.

3.1 Natural gas on the North Slope of Alaska

The North Slope of Alaska holds 23 trillion $ft^3$ of natural gas. In 1984, I originated a "North Slope Gas Concepts" program to find non-chemical means of using this resource. The strategic military location of the North Slope of Alaska and certain other unique features, such as its proximity to the magnetic pole led me to suggest that the gas be used to power the conceptual system shown in figure 3 to modify the ionosphere and to provide power for space vehicles. (Ref. 2-4, 19-21)

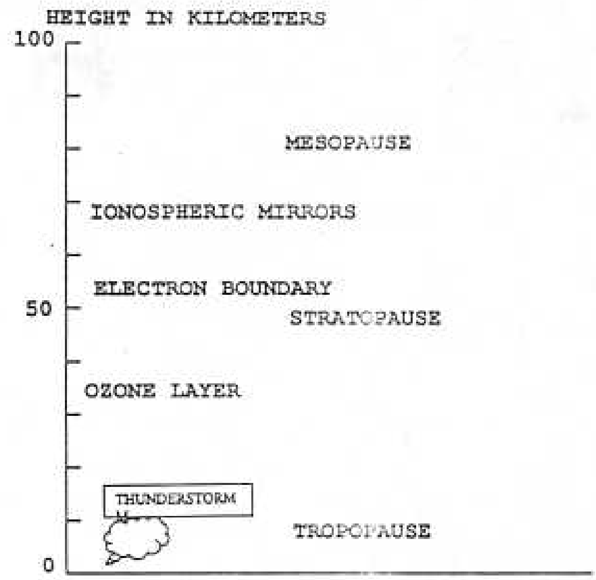


FIGURE 2

*Location of various regions and phenomena as a function of altitude in km.*

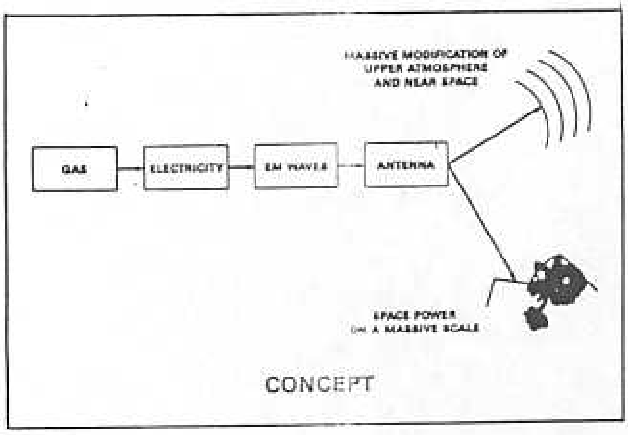


FIGURE 3

*North Slope Natural Gas Concepts System Schematic*

The energy content in the gas is shown to be much greater than the total stored energy of the ionosphere in Table 2 .The availability of the large natural gas energy source made it possible to conceive of various ionospheric modification concepts with required power levels between $10^6$ and $10^{12}$ watts.

TABLE 2

| PHENOMENA | ENERGY (JOULES) |
|---|---|
| 28 TCF NATURAL GAS | $3 \times 10^{19}$ |
| TOTAL GEOMAGNETIC ENERGY | $8 \times 10^{17}$ |
| ONE YEAR OF US ELECTRICITY | $3 \times 10^{19}$ |
| ONE DAY OF A HURRICANE | $2 \times 10^{19}$ |
| SMALL THUNDERSTORM | $7 \times 10^{9}$ |

3.1 Power and Energy Requirements for Ionospheric Modification Experiments

The power and energy requirements for some of these applications are shown in Table 3. This table is a synopsis of applications and power requirements for the antenna that were developed in the North Slope Gas Concepts program. "Plumes" are described under section 4 below. Communication control requires relatively modest amounts of power (Refs. 2-4). The creation of ionospheric mirrors require relatively more power and energy. (Ref. 2-4, 16). (Ionospheric Mirrors are shaped regions of high electron density created in the ionosphere with electromagnetic waves, which are designed to be reflectors for other electromagnetic waves. i.e. a substitute for physical reflecting surfaces.)

Geophysical exploration via generation of ELF and VLF waves requires relatively modest amounts of power. Probing for tunnels with ELF waves generated with the HAARP antenna have been reported. (Ref 17).

TABLE 3

| APPLICATION | ALTITUDE | WATTS/ $CM^2$ | ENERGY (JOULES) |
|---|---|---|---|
| PLUMES | 1000 KM | 1 | $1 \times 10^{13}$ |
| COMMUNICATION CONTROL | 50 KM | .1 | $1 \times 10^{8}$ |
| IONOSPHERIC MIRRORS | 80 KM | .1 | $1 \times 10^{8}$ |
| GEOPHYSICAL EXPLORATION | 50 KM | .01 | $1 \times 10^{7}$ |

3.2 Terawatt Antenna for Relativistic Electron Generation In the Ionosphere

The largest energy consuming application was the generation of relativistic electrons in locations of the magnetosphere where they can be trapped like Van Allen belt electrons and provide either full or partial missile shields. (Ref. 8) This application area required a power flux of 1 watt/$cm^2$ at a 150 kilometer altitude, over an area of about 10 km x 10 km for a period of about 20 minutes. This resulted in the specification for a terawatt phased array antenna 20 km x 20 km. with other properties detailed in Table 4. Subsequent work supported by DARPA has confirmed some of these numbers For example, acceleration to Mev energies was studied and theoretical predictions show that at about 1 watt/$cm^2$ electrons may be accelerated to as high as 5 Mev. (Ref. 18)

TABLE 4

REQUIREMENTS FOR MISSILE SHIELD ANTENNA

| | |
|---|---|
| POWER: | 100 to $10^6$ Megawatts |
| FREQUENCY: | 1.6, 3.2, 10-150 Mhz |
| RANGE: | 100 to 500 KM |
| TOTAL ENERGY: | $10^{14}$ to $10^{19}$ Joules |
| ENERGY FLUX AT ALTITUDE: | 1 to $10^3$ Watts/$cm^2$ |

3.3 Technology Development of Large Phased Array Antenna

Phased array radio telescopes with baselines of more than 20 km have been developed for astrophysics. Phased arrays for delivery of large amounts of power have also recently been constructed.

The HAARP antenna, in Gakona, Alaska is presently operating at 980 kw with dimensions of 168 m x 219 m and is scheduled to be upgraded to 3.6 Mw with dimensions of 316 m x 390 m in 1999. (Ref. 19)

3.4 Safety and Legal/political considerations

The pursuit of these large antenna applications in the 1980's was encouraged by DOD agencies. However, in July, 1986, a consultant on the North Slope Gas Concepts project from the University of Alaska expressed the following comments:

" As soon as information on any of the projects becomes known to residents of the North Slope Borough, it will trigger a strong reaction of concerns. Depending on what information reaches the public domain, there will be concern about the construction of large systems in the tundra; concern about the operation of large or numerous power plants; and concerns about possible effects of electromagnetic radiation fields. However justified or unjustified these concerns might be, they will be voiced passionately, perhaps even stridently. The Inuit Circumpolar Conference (ICC) would no doubt get into the picture and "internationalize" the issue, soliciting support from members in Canada and Greenland. Classification of the entire project by DOD at an early stage would help prevent surprises at a later stage (but it should be clear that concealment or credible cover-up would be essentially impossible." and

" Tampering with the space environment has come up from time to time at International non-governmental organizations (e. g.

COSPAR) and at the U. N. In recent years, it has been pretty quiet on this front, but SDI and ASAT are reviving international discussions. I expect increasing activisim on the subject; if and when the concepts of operational trapped particle dumping, ionospheric modification, and of the killer shield become widely known, a very strong international reaction could be expected and a direct intervention of the U. N. should not be ruled out."

The above comments have proven to be prophetic. Since the large HAARP phased array was constructed in Alaska, there have been intense protests by local Alaska environmentalists as to the safety and intent of the project. (Ref. 20). Since so much reaction has accompanied the HAARP project, which is to be rated at 3.6 Megawatts cw, compared to the 100 megawatts to 1 terrawatt of the initial North Slope Gas Concepts idea base it is clear that international cooperation and disclosure must be obtained for future high power antenna applications no matter how beneficial they seem.

## 4.0 NORTH SLOPE GAS CONCEPTS- ENVIRONMENTAL AND WEATHER MODIFICATION

Antennas such as those described above, can also be used for modification of the trophosphere and upper stratosphere. The beams of energy can be directed at certain atmospheric phenomena and with proper choice of frequency deliver energy to specified regions. This was recognized in 1984, and a number of concepts for environmental and weather modification were proposed. (At $10^{12}$ watts, the power delivery capability of the proposed antenna was comparable to that of a large mesocyclone.)

### 4.1 High Altitude Winds and Electron Cyclotron Resonance

Electromagnetic wave interactions at electron cyclotron resonance with electrons at altitudes of 60 to 80 km are capable of accelerating the electrons and entrained ions and neutral atoms and molecules in the vertical direction via the "mirror force" in the earth's diverging magnetic field. (The North Slope of Alaska is near the earth's magnetic pole) "Plumes" of atmosphere could be produced in this manner. At a power level of $10^{12}$ watts, there is sufficient energy to push the upper atmosphere in the vertical direction with a total kinetic energy of about $3.6 \times 10^{15}$ joules in a one hour period. This would equal the kinetic energy in the zonal winds at 80 km altitude in a volume 10km thick x 70 km wide encircling the pole.

It has been suggested that these upper atmosphere winds can couple to the lower altitude jet stream. (Ref. 21) Balsley et al have studied the modulation of the auroral electrojet and found correlation with modulation of the zonal winds at 88km altitude. (Ref. 22). The HAARP antenna modulates the auroral electrojet to induce ELF waves and thus could have an effect on the zonal winds. (Ref. 19)

### 4.2 Ozone production from 30 to 40 km

In 1986, evidence for an ozone hole in the arctic region was mounting. Two aspects of large electromagnetic wave antennas were seen to be relevant to the study of possible ozone hole mitigation effects. First, electric breakdown of the air from focused beams of electromagnetic radiation could be a source of ozone production. Electrical discharges are routinely used for ozone generation. (Ref. 23) This concept has recently been pursued by Smakhtin and Rybakov. (Ref. 24)

Second, acceleration of ions from the upper atmosphere into the ionosphere as described in plume formation was also considered in Refs. 2-4. Recently, Wong et al have suggested that large antennas in Alaska could accelerate $Cl^-$ ions out of the atmosphere. (Ref. 25)

### 4.3 Power Relay Ionospheric Mirrors

One application of North Slope antennas was to beam power to satellites at 36 Ghz, to make use of a "window" in the earth's atmosphere. This frequency range would permit smaller rectennas than the 2.5 Ghz previousely considered.

Ionospheric mirrors were also considered (Ref. 2-4, 16) as a means of reflecting power from one earth based location to another without the use of satellites. The HAARP program is investigating formation of reflecting layers and plasma "lenses" in the ionosphere. (Ref. 26)

## 5.0 HIGH POWER SATELLITE SOURCES

### 5.1 Solar Power Satellites

Solar power satellites were developed by Glacier in 1979 (Ref.27) and have been pursued in various NASA, ESA and other international programs (Ref. 28). Typical planned power levels are 3000 to10000 megawatts, which is in the mid-range of the power levels suggested in the North Slope Gas Concepts regime. As opposed to a facility located in one geographical location, such as the North Slope of Alaska, satellite systems in geosynchronous or lower orbits could extend the range of applicability of weather modification ideas.

## 6.0 SYSTEMS FOR SEVERE WEATHER MODIFICATION

The large antenna systems described above, although they are primarily conceptual studies, have sparked further interest in their potential for severe weather modification.

Intense electromagnetic wave beams can be powered by ground based energy sources, such as natural gas and by solar power generated on satellites. Two basic interaction mechanisms can be used to modify severe storms. Microwaves absorb in rain and in atmospheric components such as $O_2$, $CO_2$and $H_2O$. Figure 4 shows attenuation as a function of frequency and rainfall rate. (Ref. 38) Based on this physics, it can be seen that beams in this frequency regime can be directed at a severe weather pattern from space, or from a ground based transmitter and absorb primarily in the regions of the storm with high rain content. Clear air, such as in the jet stream or in the regions around a storm, can be heated by absorption in the atmospheric components. Figure 5 shows the attenuation in clear air as a function of frequency. (Ref. 38)

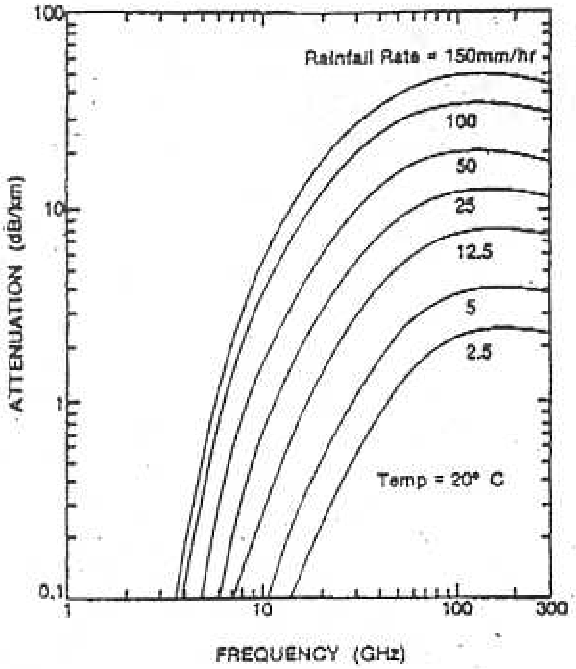


FIGURE 4

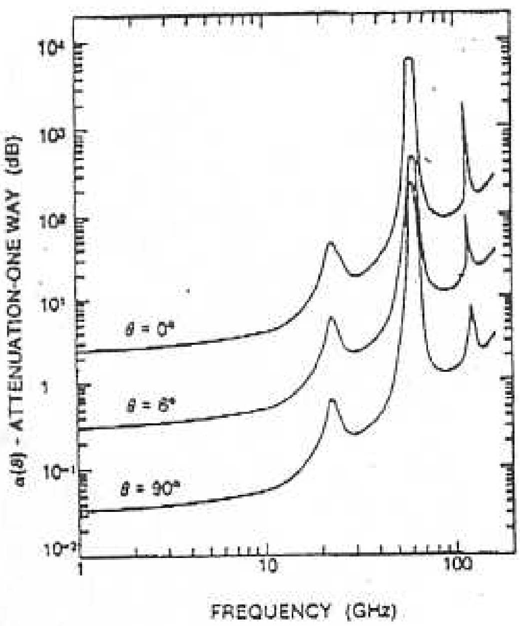


FIGURE 5

We choose tornadic thunderstorms as an initial area of severe storm modification research because they are in the low range of storm energy turnover (See Table 1). We also choose to center our initial concept on use of a modified solar power satellite, which we call the "Thunderstorm Solar Power Satellite" (TSPS) because solar power satellites have been designed at comparable power levels of $10^{10}$ watts.

6.1 Tornadogenesis in Mesocyclones

Grazulis (Ref. 29) describes tornadoes as follows:

" Tornados are one of the most intensely violent phenomena on the planet, and even a small tornado can be a spectacular sight. larger ones can operate with energy in the same order of magnitude as a large nuclear power station, and yet consist of little more than a blend of insubstantial air and water vapor. A tornado can be thought of as a simple vortex, a rotating, spiraling fluid, like those in a draining sink or bath tub. But behind that apparent simplicity lies a mind-boggeling complexity of fluid dynamics, air/moisture interactions, and energy transfers. Yet, a tornado is just a fluid. There are no mysterious forces at work here. "

Tornadic thunderstorms are responsible for considerable property damage and loss of life in the United States. Figure 6 from Ref. 29 illustrates the average annual loss of life and Table 5 represents the frequency of occurrence. Not all mesocyclones produce tornadoes and the detailed study of the formation of a tornado from a mesocyclone is a young science (Ref. 5,9-10) and the "cause" of tornadogenesis is still not clearly known. However, suspicion is centered on the cold, rain-laden downdraft that occurs next to the updraft that initiates formation of the mesocyclone.

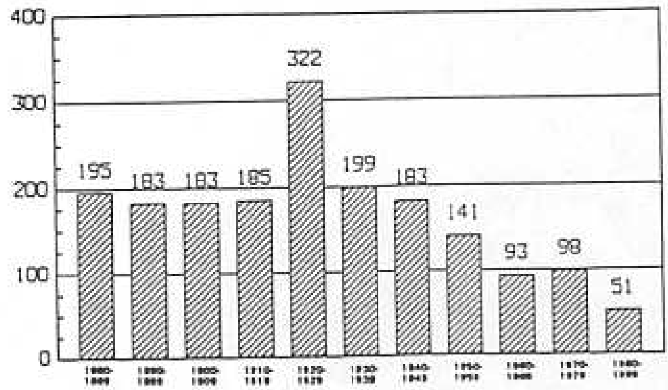


FIGURE 6

Figure 7 is a schematic view of a tornadic thunderstorm near the surface. (Ref. 10). The thick line encompasses the radar "hook echo". The barbed line denotes the boundary between the warm inflow and the cold outflow and illustrates the occluding gust front. Low-level position of the updraft is finely stippled, while the forward-flank and rear-flank downdrafts are coarsely stippled. Storm-relative surface flow is shown along with the likely location of tornadoes (encircled T's)

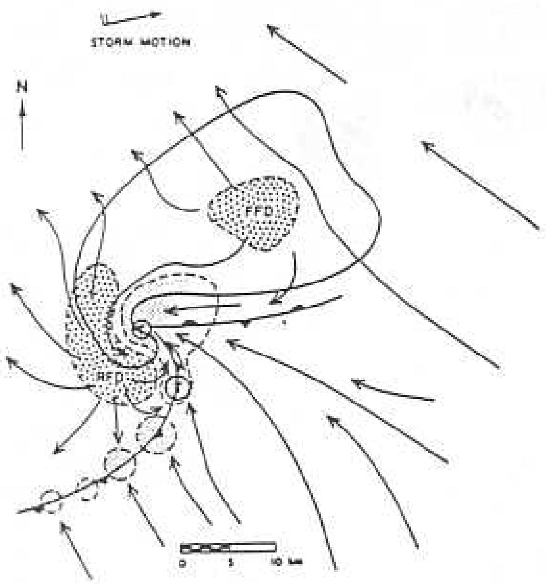


FIGURE 7

*Schematic view of a tornadic thunderstorm near the surface.*

For a tornado to form, flow parameters such as vertical and horizontal vorticity must be in a narrow range. We investigate such systems in more detail below to identify "fine structure" that could be heated by electromagnetic waves and interfere with the ability of a storm to organize a tornado. We also intend to determine the requirements for meaningful intervention in tornadogenesis.

6.1 A Concept for Intervention in Tornadogenesis

A specific concept for intervention in tornadogenesis with a Solar Power Satellite is shown in figure 8. This suggested "Thunderstorm Solar Power Satellite" (TSPS) would have adaptive diagnostic systems for detailed measurement of the storm system and large phased arrays for focusing the power on specific regions of the storm. (It would be designed for transmission of power for use in an earth based power grid when not used for severe storm mitigation.) The WRS-88D Doppler radar system presently installed for ground based detection of tornadic systems would also be used. ( Ref.6)

Step 1. The WRS-88D Doppler radar would identify a forming storm system, and locate the regions of highest rainfall and vorticity to a resolution of 2 to 10 km.

Step 2. The TSPS adaptive diagnostics would receive location information on the storm from the ground based system and then use downlooking doppler radar systems with resolution of about 50 m to measure vertical velocity components of the downdraft and updraft regions of the storm. (Note, that this would be valuable as an aid to weather prediction models, which presently have to rely on vertical motion data that is inferred from horizontal motion data from the WSR-88D Doppler radar.)

Step 3. Numerical models would digest the information from the weather diagnostic systems. (These would be improved numerical modes and based on a research program designed to assure international review committees that the model is sufficiently well developed to determine the consequences of heating experiments.) Instructions would then be given to the power beam control system for directing the beam to the appropriate region of the storm.

Step 4. The cold downdraft would be heated in such a way as to cancel the horizontal thermal gradients that develop between the downdraft and the updraft, hopefully terminating the development of a tornado.

Thus, by heating key elements of the "fine structure" of a storm, the formation of tornadoes might be mitigated, providing appropriate systems can be developed. However, these storm systems are highly complex and the severity of the storm might also be increased. For this reason, we have undertaken a careful systems study to determine the safest way to pursue the concept.

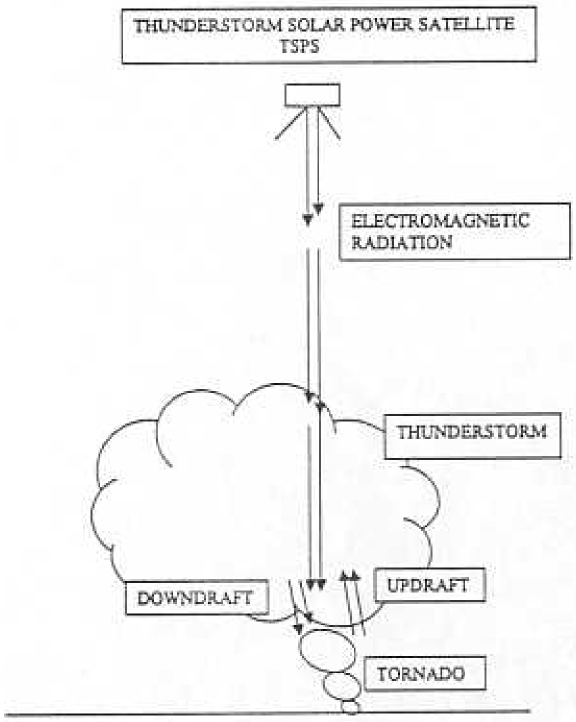


FIGURE 8

*A drawing of a concept for severe storm mitigation. An orbiting "Thunderstorm Solar Power Satellite would provide diagnostic information on the location of cold, rainy downdrafts and then direct high power beams of electromagnetic radiation for heating of the downdraft regions, leading to elimination of temperature gradients with the "hook echo" region of the storm and possibly interfering with the formation of tornadoes.*

7.0 TOP LEVEL SYSTEM FUNCTIONAL FLOW

We examine the feasibility of prevention of formation of tornadoes in mesocyclones and estimate the power requirements for such mitigation. Our hypotheses is that by heating cold, rainy downdrafts near the "hook echo" we can eliminate the downdraft and disturb the precise set of conditions necessary for tornado formation.

The top level system functional flow is shown in figure 9. The purpose of this section is to describe the technology required for each subsystem and to determine the requirements for accomplishing severe weather mitigation. The requirements for each system element are developed in this section:

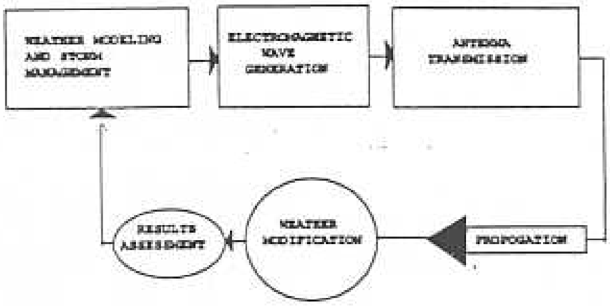


FIGURE 9

*Top Level System Functional Flow.*

7.1 Weather Modeling and Storm Measurement

Numerical weather modeling must be sufficiently well developed to provide storm-scale weather prediction in real time based on input from an array of appropriate sensors. Our analysis is based on the use of the ARPS code mentioned above. (Ref. 15) This model has been developed over a period of years, and has been used for tornadogenesis studies (Ref. 9) However, emphasis on tornadogenesis has been minimal, with most of the research being devoted to weather prediction.

The governing equations have been described above.We have modified the code to study heating by electromagnetic waves as follows. A subroutine is inserted which assumes an arbitrary level of heating, in terms of specified values for °K/s-m$^3$. The level of heating is then specified as a function of rain content. i.e. the electromagnetic waves absorb preferentially in the highest rainfall regions. At each time step of the calculation, we compute the total volume of rainfall, which, with the heating rate known, allows us to calculate the total power usage.

7.1.1 May 20, 1977 Del City Baseline Storm

The May 20, 1977 Del City storm (Ref. 30) is used as a baseline storm in the ARPS code. The code initiates with a "bubble" of warm air with a temperature rise 10 °F above ambient, with its base at an altitude of 1 km and with a 10 km diameter. Further specifications of the wind direction and velocity as a function of altitude correspond to balloon soundings for that date and location. Note that a nested grid structure, in which the grid size is reduced to 58 meters in the region of tornado formation was used by Xue (Ref. 9). His results on a 1 km horizontal grid are shown in Figure 10. This figure depicts the low level, 250 meter flow fields.. The "hook echo" region shows clearly in Figure 11, which is the same region with a 58 meter grid. A "hook-echo" feature, identified by the large arrow, is similar to the "hook-echo" boundary in figure 8, along which tornadoes can be expected to form.

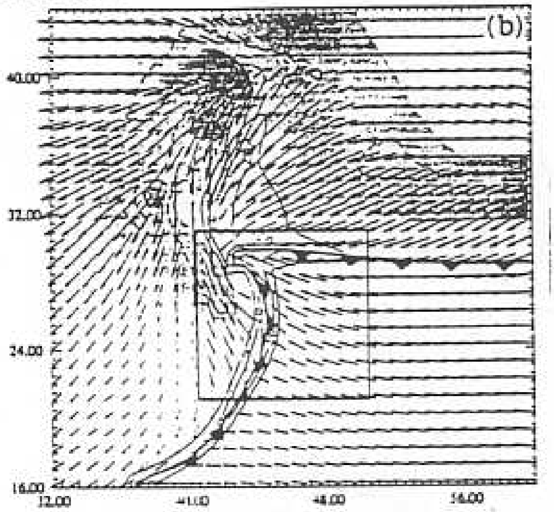


FIGURE 10

*Low level flow fields, areas within which the rainwater content is greater than 0.5 g/Kg and 5.0 g/Kg are shaded with different density. The gust front location is depicted by the 1.0 K potential temperature perturbation contours drawn with the standard cold front symbols, the other dashed and solid contours are for w, the vertical velocity, at an 1 m/s interval. The wind vector scale is shown in the figure.*

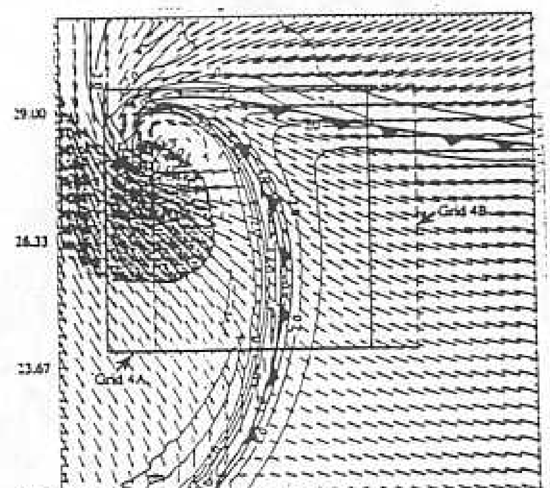


FIGURE 11

*As in figure 10, but with a grid resolution of 56m.*

Rainfall begins to develop at about the 20 minute point in the simulation. By one and one half hours, the above "hook echo" features that are thought to represent the conditions needed for tornado development begin to form.

7.1.2 Base Case for Intervention Studies

We also use May 20, 1977 storm for our intervention investigation. In our case, the ARPS code was run only with a 1 km horizontal grid and a 300 meter vertical grid. The fine grids typical of Figure 11 take much more time and such fine grid examinations are deferred. The Cray J90 at CAPS was used for the calculations. Figures 12a, 13a and 14a show the results for the simulation at an altitude of 250 meters and 5400 seconds after initiation of the simulation. Figure 12a shows the temperature contours in °K and the small vectors indicate the difference between horizontal velocities in the x and y direction in meters/second. This term is an indication of vorticity. Note that the "hook echo" patterns are clearly visible. Figure 13a indicates the vertical velocity contours in meters/second. The downward velocities are denoted by dashed lines. Notice that they are situated near the "hook echoes". Rainfall is indicated in figure 14a. Contours are in g/Kg. (Note figure arrays are grouped by parameter for easier comparisons.)

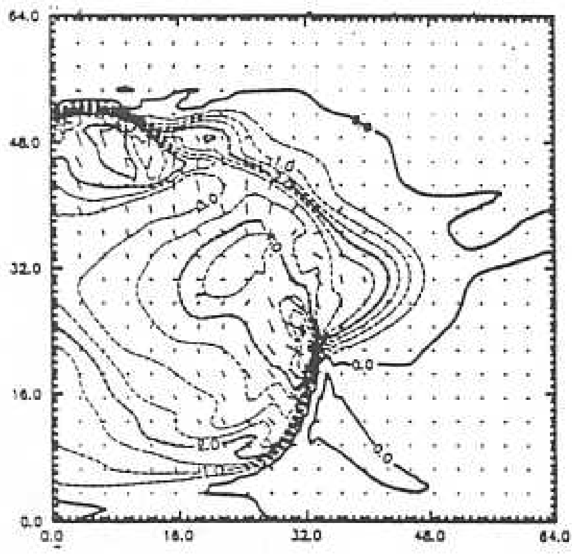


FIGURE 12a

*Base Case. Temperature contours and difference between horizontal and velocity vectors*

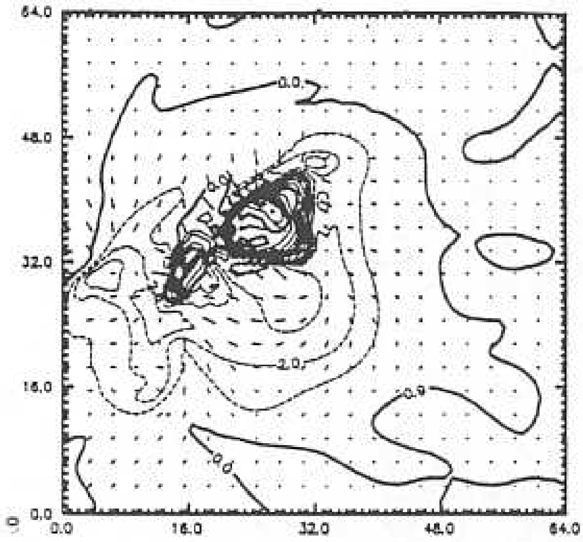


FIGURE 12b

*Heating .05 °K/s/m³ in 2 g/Kg rain, continuous from initiation of storm. Temperature contours and horizontal velocity vectors.*

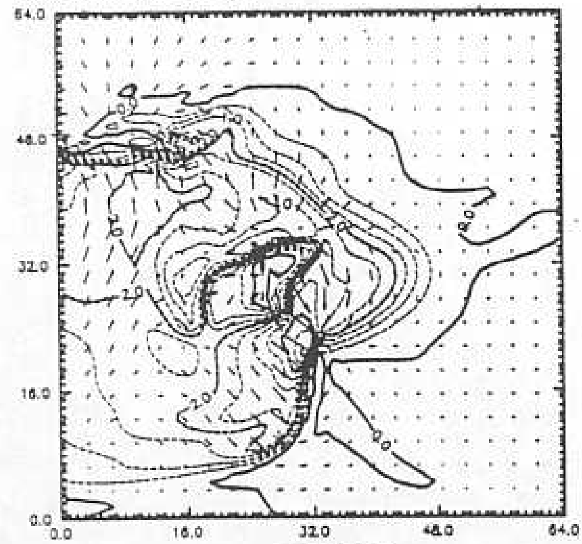


FIGURE 12c

*Heating rate of .02 °K/s/m³ in 2 g/Kg rain, initiated at one hour into the storm development. Temperature contours and horizontal velocity vectors.*

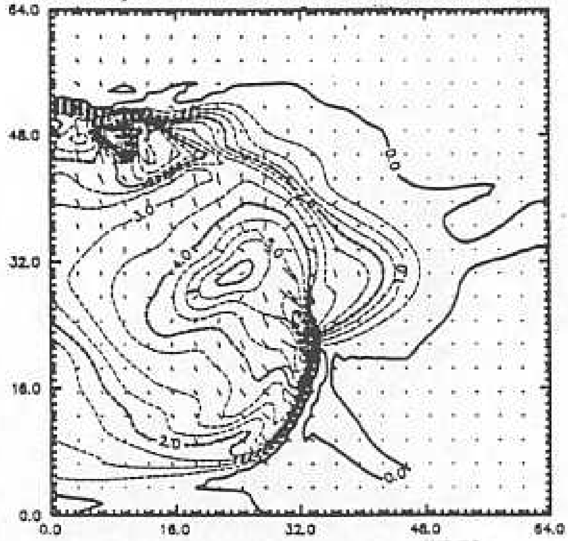


FIGURE 12d

*Heating rate of .05 °K/s/m³ in 6 g/Kg rain, initiated at one hour into the storm. Temperature Contours and horizontal velocity vectors.*

7.1.3Heating rate .05 °K/s-m$^3$ with Rain Content of 2 g/Kg.

If the cold, rainy downdraft in the "hook echo" can be heated, then elimination of the downdraft and resultant thermal gradients in this region could be an indication of the feasibility of mitigating the formation of tornadoes.

In this case, a high heating rate of .05 °K/s was turned on continuously from the inception of the storm. The heating was applied to all regions with a rainwater density of 2 g/Kg or greater. There was no power absorbed until about the 20 minute point, when rain started to form. The modification in this case was massive. Figure 12b above shows the temperature contours in °K with the small vectors indicating the vorticity. Note that in comparison with 12a above, the "hook-echo" region has been eliminated and replaced with closed isotherms in a central region. Figure 13b shows the vertical velocity contours with a dramatically changed pattern, from Figure 13a, the base case. Finally, in Figure 14b, the rainfall appears to have been reduced compared to Figure 14a, the base case.

In this example, a volume of about 100 km$^3$ was heated at a rate of .05 °K/second and the total power delivered was about $10^{13}$ watts.

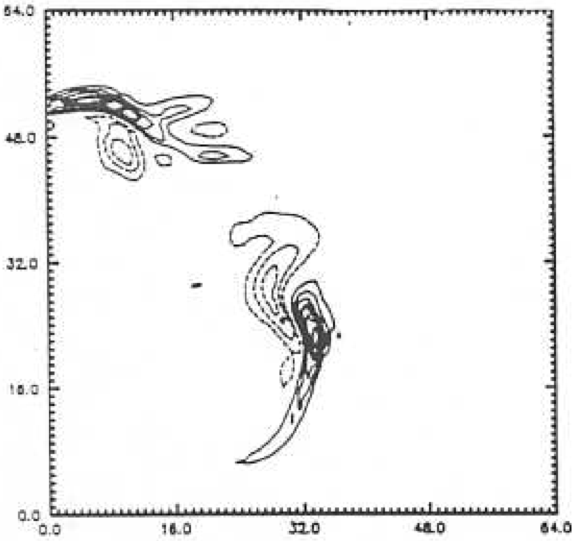


FIGURE 13a

*Base Case. Vertical velocity contours in meters/second.*

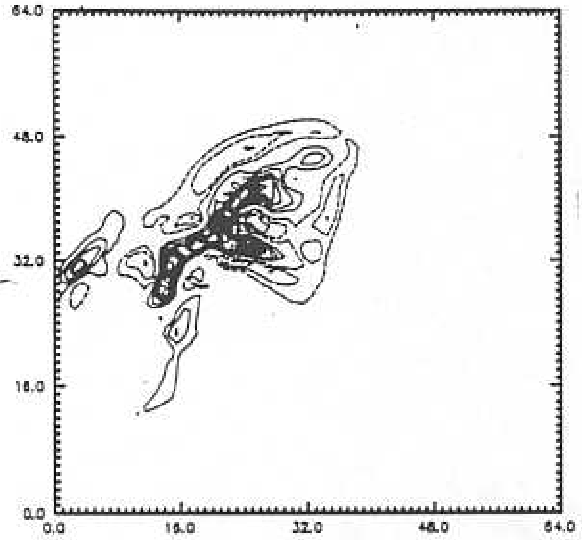


FIGURE 13b

*Heating .05 °K/s/m$^3$ in 2 g/Kg rain,continuous from initiation of storm. Vertical velocity contours in meters/second.*

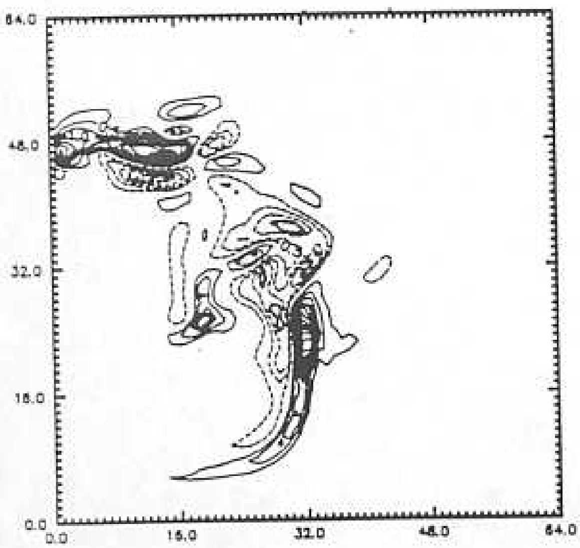


FIGURE 13c

*Heating rate of .02 °K/s/m$^3$ in 2 g/Kg rain, initiated at one hour into the storm development. Vertical velocity contours in meters/second.*

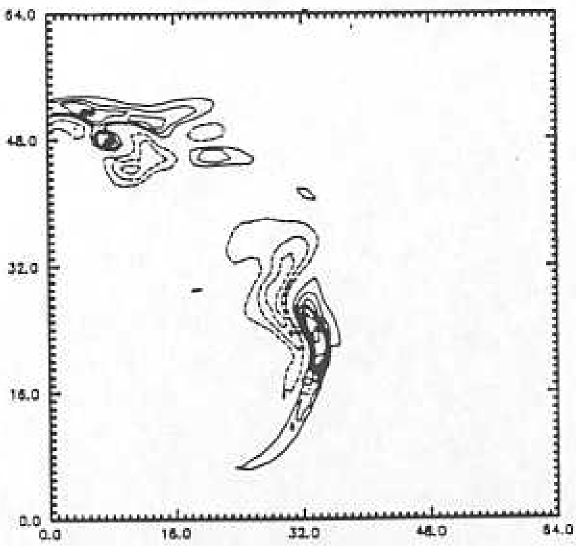


FIGURE 13d

*Heating rate of .05 °K/s/m$^3$ in 6 g/Kg rain, initiated at one hour into the storm. Vertical velocity contours in meters/second.*

7.1.4 Heating rate .02 °K/s-m³ with Rain Content of 2 g/Kg.

At a lower power of .02 °K/s-m³ with Rain Content of 2 g/Kg, heating was initiated at the one hour point of the storm's development. These results also had an observable effect on the storm.

Figure 12c shows the temperature contours and the vorticity vectors. Note that the "hook echoes" appear diminished and the temperature has risen in the downdraft region, compared to 12a. Figure 13c, the updraft velocities, shows updrafts in regions which had been downdrafts in Figure 13a. Finally, the total rainfall in Figure 14c seems to have decreased compared to the base case in Figure 14a also.

In this case, a volume of about 100 km³ was heated at a rate of .02 °K/second and the total power applied is about 3 x $10^{12}$ watts.

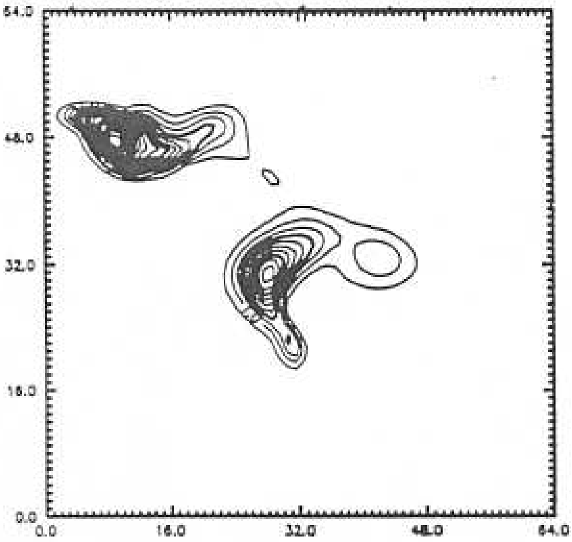

FIGURE 14a
*Base Case. Rainwater density contours in g/Kg.*

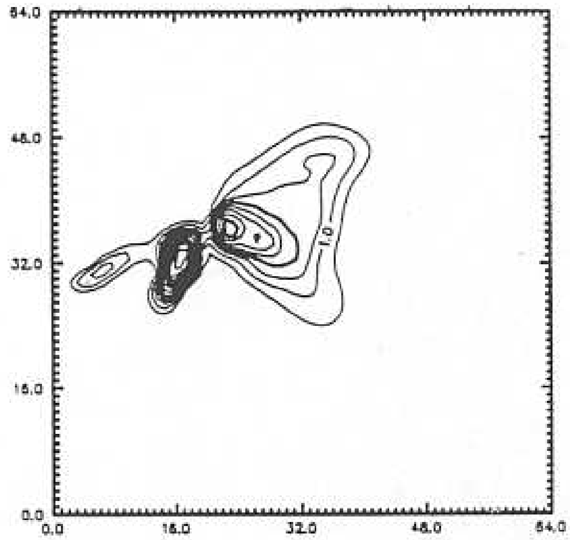

FIGURE 14b
*Heating .05 °K/s/m³ in 2 g/Kg rain,continuous from initiation of storm. Rainwater density in g/Kg.*

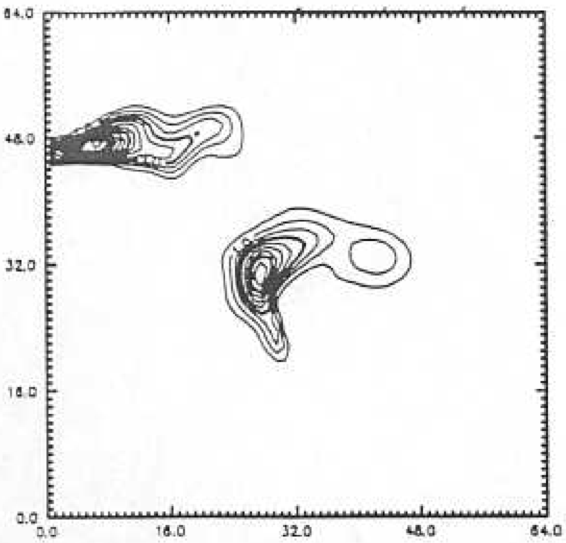

FIGURE 14c
*Heating rate of .02 °K/s/m³ in 2 g/Kg rain, initiated at one hour into the storm development. Rainwater density in g/Kg.*

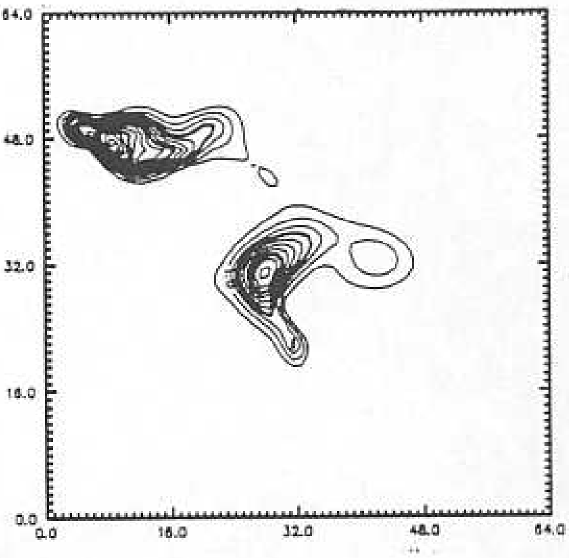

FIGURE 14d
*Heating rate of .05 °K/s/m³ in 6 g/Kg rain, initiated at one hour into the storm. Rainwater density in g/Kg.*

7.1.5 Heating rate .04 °K/s-m$^3$ with Rain Content of 6 g/Kg.

At a higher power of .04 °K/s-m$^3$ with Rain Content of 6 g/Kg, heating was initiated at the one hour point of the storm's development. These results also had a smaller, but observable effect on the storm.

Figure 12d shows the temperature contours and the vorticity vectors. Note that the "hook echoes" appear slightly more pronounced and the downdraft region has heated compared to 12a, the base case. Figure 13d, the updraft velocities, shows small changes in the center region compared to 13a. Finally, in figure 14d the total rainfall seems to have decreased compared to 14a.

In this case the volume was 0.5 km$^3$ and the total power was about $5 \times 10^{10}$ watts.

7.1.6 Estimates of Max and Min Power Required

This is a very large, base case storm. Some tornado generating mesocyclones can be one tenth the dimensions of this storm. Thus, the power requirements for the modifications described above range from about $5 \times 10^9$ to $10^{11}$ watts for heating based solely on rainfall amounts.

Other factors could further decrease the power required. In these calculations we heated all the volume with a rain content greater than a specific value. Because the phased arrays could be focused on features as small as 50 meters, specific regions of the rainfall could be heated. For example, the cold region in the "hook-echo" boundary might be targeted. For a given storm, this region would be 1/10th the volume of the calculations above. Thus the power levels required for meaningful modification of a storm could have a lower range of $5 \times 10^8$ to $10^{10}$ watts.

7.1.8 Requirements for Downdraft Elimination

Heating Volume

The volume heated can range from less than 1 to more than 100 km$^3$. This leads to linear dimensions of from a few hundred meters to 10 km. Specifically, the region of high rain fall of 6g/Kg or more is about .5 km$^3$.

Rainfall Density and Rate

The rainfall density in the downdrafts can be assumed to range between 2 g/Kg and 6 g/Kg. (2g/Kg corresponds to a rainfall rate of about 50 mm/hour and 6g/Kg corresponds to a rainfall rate of 150 mm/hour.)

Heating Rate

Heating rates of .01 °K/second-meter$^3$ to .05 °K/second-meter$^3$ appear adequate for significant heating on time scales of 30 minutes.

Total Power

The maximum range for the total power is estimated to be from $5 \times 10^9$ to $19^{11}$ watts and the minimum range is estimated as $5 \times 10^8$ to $10^{10}$ watts.

7.2 Electromagnetic Wave Generation

7.2.1 Energy Source and Power Generation

For this discussion, it is assumed that the source of energy for the SPS is solar power. The energy received from the sun is converted into electricity via solar cells, which are then used to power electromagnetic wave generators.

7.2.2 Frequency Choices

Figure 4 is describes the attenuation coefficient of microwaves in dB/km as a function of frequency. The requirement of heating lengths on the order of 100's of meters to 10 km can be met by appropriate choice of transmitter frequency.

We choose a 500 meter and a 1 km length to illustrate how this leads to the choice of frequency for the microwave generator. Attenuation over a distance of 1 km is 90% at 10 dB and at 20 dB the attenuation is 90% over a distance of 500 meters.

Using Figure 4, we find that at a rainfall rate of 150 mm/hour and a frequency of 12 Ghz the attenuation is 10 dB and at 22 Ghz the attenuation is 20 dB. At a rainfall rate of 50 mm/hour the attenuation is 10 dB at 40 Ghz and is 20 dB at about 96 Ghz.

7.2.3 Power Flux

The power flux is determined by the heating rate requirements of .01-.05 °K/second-meter$^3$. Approximately 2,000 Joules/meter$^3$ is required to raise the temperature of a cubic meter of sea level air by 1 °K. With an attenuation length of 1 Km a heating rate of 1 °K/second-meter$^3$ requires an incident flux of $2 \times 10^4$ watts/m$^2$. For an absorption length of 500 meters the flux requirement becomes $10^4$ watts/m$^2$. (About 7 times the solar flux.)

7.2.4 Microwave Generators

SPS studies have centered around 2.5 Ghz because of the availability of inexpensive magnetrons. ( A consequence of the low prices brought about by the large microwave oven market.) More recently, Matsumoto et al (Ref. 31) proposed a design of a Power Supply Satellite with solid state amplifiers at 24 Ghz.

Millimeter wave gyrotrons have been developed and applied to plasma heating in Tokamak fusion research devices. (Ref. 32) Granatstein has recently reviewed gyrotron research and development. (Ref. 33) Figure 14 is taken from Ref. 33. This figure describes the average power density available from a single microwave power tube as a function of time. Progress has come at a rate exceeding an order of magnitude increase per decade. Gyrotrons have been developed in which individual tubes can produce 0.5 Mw for 2 seconds at 110 Ghz. (Ref. 34)

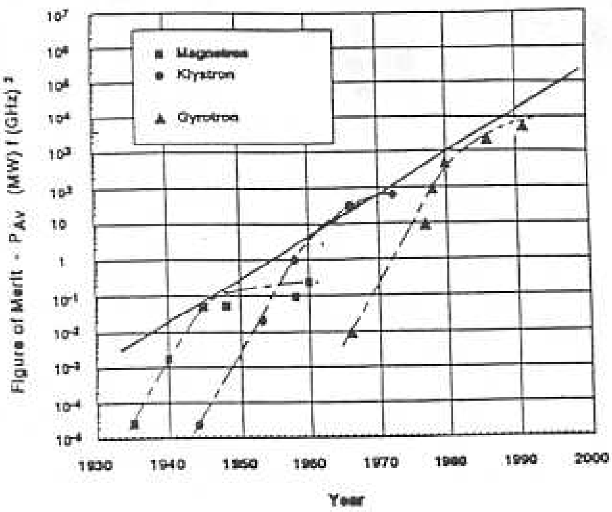


FIGURE 14

*Average power density potential of a single microwave tube versus year.*

The electrostatic-accelerator free-electron laser (EA-FEL) has been designed for operation in the atmospheric "windows' of 35, 94, 130 and 220 Ghz. FEL devices have been studied for power beaming applications. (Ref. 35)

7.2.5 Microwave Generator Requirements

Individual Power Tubes

Frequency: 6-96 Ghz
Pulse Duration: 10 - 30 minutes

Power Tube Arrays

Power Level $10^8$ - $10^{10}$ watts

7.3 Antenna Transmission

It is too early to decide on the orbit of the TSPS. The TSPS could have a dual use. It could be used for generation of power on land via rectennas when it is not in use intervening in tornado formation. Thus, we discuss both geosynchronous and orbital locations in assessing the size of the requisite antenna.

The basic relationship between between antenna aperture and focal spot size is as follows:

$$r = \left[\frac{R^2}{2} - \frac{\lambda}{2\cdot\pi}\cdot\left[\left(\pi\cdot\frac{R^2}{\lambda}\right)^2 - (2\cdot h)^2\right]^{.5}\right]^{.5} \quad (1)$$

where: r = Focal Spot Radius

R = Aperture radius

h = Distance from Aperture to Focal Spot

$\lambda$ = Wavelength of Radiation

7.3.1 Diagnostic Radar

7.3.1.1 Doppler Radar

The WSR-88D doppler radar system has a beam width of 9° and a typical resolution of 1 - 10 Km. This would be adequate in step one of our concept, to locate a candidate mesocylone. The TSPS would be designed with a doppler radar imaging systems to identify and quantify the velocity of the rain the downdraft.

The TSPS system must be able to distinguish rainwater densities of between 2 and 6 g/Kg. Spatial resolution of 10-50 meters will be desirable.

At geosynchronous orbit, a 36 Ghz Doppler Radar with an aperture radius of about 2 km would give a focal spot radius of about 50 meters.

At an orbit of about 800 km, an aperture radius of about 70 meters would give a focal spot radius of about 50 meters.

7.3.1.2 Microwave Radiometers

Microwave radiometers with 10-50 meter resolution would also be included to measure the temperature distribution within the mesocyclone.

7.3.2 Power Antenna

At geosynchronous orbit, the original SPS study (Ref. 27 ) gave antenna dimensions of 10 km x 5 km with an earth based rectenna of 5 km radius.

From the discussion of weather requirements, we see that the TSPS antenna needs to irradiate a target of about 1 Km in diameter. At 12 Ghz, for example, this would require an antenna aperture of about 800 meter radius for geosynchronous orbit. At an orbit of 800 km altitude, the antenna dimension would be close to the focal spot size. Note, that at mm wavelengths, the spot size could be much smaller than 1 km. Thus, raster type illumination would be possible.

A lower earth orbit would not provide 24 hour coverage, but might be useful for an initial development effort to validate the concept.

7.3.1 Antenna Requirements

Doppler Radar

Frequency: 10 - 96 Ghz
Power Flux: 10 Mw or greater

Response Time: Milliseconds
Spatial Resolution: 10-50 meters

Radiometer:

Response Time: Milliseconds
Spatial Resolution: 10-50 meters

Power Phased Array

Frequency: 10 - 96 Ghz
Power Flux: $10^8$ - $10^{10}$
Dimensions: Function of frequency
Agility: Reposition Beam in Microseconds

7.4 Propagation

The SPS (Ref. 27 ) was to be targeted on the rectenna receiving array via locking on a signal from a transmitter located at the rectenna array. Targeting a specific cold, rainy downdraft in a mesocyclone will be difficult, because the downdraft can have a horizontal velocity of up to 70 m/sec and it is imbedded in a complex mesocyclone system.

The diagnostic package of the TSPS will need to reliably locate this downdraft on a time scale of about 1 second.

If this requirement can not be met using the diagnostic package on the TSPS, then enhancements to the WSR88D, including increasing the number of radars and adding a radiometry capability may be necessary.

7.4.2 Overburden

As can be seen in Figure 9, there could be considerable cloud and rain cover over the downdraft region we wish to heat. The region we wish to heat will most likely have the highest rainfall concentration. For example, if the rainfall in the top of the cloud is below 2 g/Kg, then there will be little attenuation before the beam enters the higher rainfall volumes.

It would also be possible to direct the beam to the heating region at an azimuth angle less than 90 degrees. Figure 5 shows that the attenuation at angles down to 6 degrees can be quite small at many of the frequencies under consideration.

7.5 Results Assessment

The diagnostic packages on the TSPS will be essential for measuring the location and behavior of the storm and the results will be fed back appropriately to control the operation of the power phased array antenna.

8.0 SAFETY

The SPS was designed to have a flux at the rectenna of about 150 watts/meter$^2$. If the downdraft is irradiated by a single beam, then it would be supplying a flux of about $10^4$ watts/meter$^2$. With an attenuation of 20 dB that would drop to the 100 watts/meter$^2$ range.

8.1.1 Bioeffects

The AMPI regulations for limits on continuous microwave exposure from microwave ovens is that the flux within 5 cm of the door must be below 50 watts/meter$^2$. Thus, with the 20 dB absorption, the beam could be safe for use. However, even though the beam would be carefully controlled, a miss could still be dangerous biologically. If the beam or beams miss the downdraft, then until the deviation is detected and the beam turned off, power levels of a kilowatt/meter$^2$ or more could strike a populated area. Note that a conventional SPS would use the wave-front reversion of the pilot-signal emitted from the center of a ground based receiving system. (Ref. 36) In the case of the TSPS, the diagnostic package must identify the storm's fine structure and direct the beams to the rainy region.

A technological solution would be to utilize a small array of TSPS satellites, and pick slant propagation paths that are nearly horizontal to the earth. The design goal would be to have the beams cross in the rainy region in the downdraft but no where else. The number of satellites and their propagation paths would be chosen so that at no time are biological safety standards exceeded on the ground.

8.1.2 Airplanes

The TSPS diagnostic package would be set up to detect an airplane approaching the propagation path of an individual beam and would turn off the power beam until it is past. Note that there will be a window of 20 minutes or so in the tornadogenesis process over which the heating process can be initiated.

8.1.3 Electromagnetic Interference

All International standards must be satisfied. These factors will be integrated with the choice of operating frequencies.

8.1.4 Legal and International Requirements

The U. N. Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification, which went into effect October 5, 1978, applies to "Widespread, long-lasting or severe environmental modifications. Local, non-permanent changes, such as precipitation enhancement, hail suppression or tornado mediation would presumably be allowed. However, it is our recommendation that the TSPS concept be reviewed by the U. N. and other appropriate international organizations from its inception.

First, the risk needs to be quantified, with appropriate studies. (Biological hazards of high frequency microwave exposure are just now being studied because these high frequencies are being used for medical applications of microwaves.) Second, the public must be involved in the development of the concept from the start. If tornadoes can be mitigated that would have incalculable benefits in saved lives and property value, but the public itself must want to accept the risks involved.

9.0 HURRICANES AND TYPHOONES

Hurricanes and typhoons have thousands of times more energy than tornadoes. They also have awesome consequences, as hurricane Andrew demonstrated. Figure 15 is a schematic of the major air flow components of a hurricane. (Ref. 37 ) Note, that cold, rainy downdrafts are a prominent feature. Also, hurricanes take days to form rather than hours, and they form as steering winds agglomerate groups of thunderstorms.

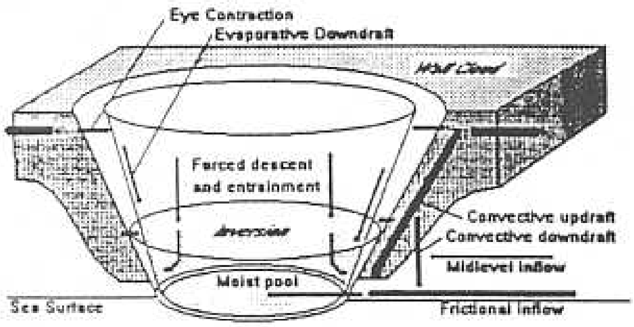


FIGURE 15

*Schematic illustration of the mass and moisture budget of the hurricane eye.*

If systems for intervention in tornadogenesis can be successfully developed, then they could form the "kernal" of systems designed for larger or more complex severe storms such as hurricanes and typhoons.

## 10.0 RESULTS OF INITIAL SYSTEMS ANALYSIS

The above systems analysis shows some gaps in the knowledge and technology base that need to be filled in before the feasibility of this concept is proven. For example, the numerical models need to be exercised in a vigorous effort to determine the fine structure and the best methods for heating. It needs to be proven that it would be possible to aim the beam or beams from a TSPS and apply the power to specific regions of a storm system. Safety needs to be further refined based on these results and the operational characteristics of the beam propagation and absorption. The appropriate legal and societal procedures need to be developed.

Initial emphasis should be on a relatively small TSPS, i.e. a 100 megawatt system that could be used as an advective diagnostic system to obtain data on vertical rainfall motion in mesocyclones. This data could be used to verify the validity of the numerical model. The power level should be adequate to create measureable perturbations in storms. These perturbation could be used further validate the models and obtain initial information on the effectiveness of the mitigation efforts.

A parallel effort to use the TSPS for power transfer experiments in a classic SPS configuration could also be included.

## 11.0 SUMMARY AND CONCLUSIONS

We have studied the potential for intervention in the process of tornadogenesis in mesocyclones. We have performed a top level functional systems analysis of a concept for intervention in tornadogenesis and have identified the issues that need to be further studied before feasibility can be shown.

We have suggested that a Thunderstorm Solar Power Satellite with a 100 MW capability could be useful in answering some of the key feasibility questions. This TSPS could be a dual use facility that also furthers fundamental SPS technology development.

We have emphasized some of the safety, societal and legal issues that would be necessary to ensure the safe development of such systems.

The system for intervention in tornadogenesis that we suggest herein is based on combining state of the art technologies of numerical weather simulation, weather diagnostics, electromagnetic generators, antenna systems, antenna control systems, satellite design and systems control. These tools are available now to help construct a new science of severe storm intervention.

Throughout history, mankind has sought to minimize the impact of the unpredictability and severity of violent storms such as tornadoes. To date, solutions have focused on development of fortified buildings made to hopefully withstand the strong forces which are the hallmark of these atmospheric events; as well as the development of sophisticated prediction methodologies to warn populations of potential climatic instability. These "warn and seek shelter" mechanisms have clearly reduced to some extent the loss of life and, to a lesser extent, property damage associated with these natural events. However, despite our best efforts, loss of life and costly property damage are still strongly associated with severe weather phenomenon. This paper has presented a new paradigm which seeks to minimize the potential development of the atmospheric conditions necessary for the formation of these violent weather systems by using beams of electromagnetic radiation from satellites to heat the fine structure, possibly preventing the formation of tornadoes, arguably the most severe weather systems on Earth.

The systems analysis in this paper is very rudimentary and much more work, especially in the areas of numerical simulation and in beam propagation analysis need to be completed before feasibility can be discussed. Additionally, any program to pursue such goals needs to rest on firm public support in which the risks and benefits are clearly set forth.

However, if it does prove to be possible, and tornadoes can be prevented, then systems could be envisioned in which severe storm phenomena such as hurricanes and typhoons are also modified in some beneficial fashion, and weather modification could be routine in the twenty first century.

ACKNOWLEDGEMENTS

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Mauro Novara 10-01-99 12:06

To: luc@grip.org
cc:
Subject: Explospace 20-22 October 1998

Dear Mr. Mampaey,

it is correct that Dr. Eastlund gave such a talk at the EXPLOSPACE Workshop in Cagliari last October, the actual title being: "SYSTEMS CONSIDERATIONS OF WEATHER MODIFICATION EXPERIMENTS USING HIGH POWER ELECTROMAGNETIC RADIATION". However, the paper was based largely on Dr. Eastlund's own experience and background work. ESA has currently no research activities concerning weather modification. ESA financial support was only aimed at supporting Dr. Eastlund's participation into the Workshop.

A study is being conducted by DLR on behalf of ESA concerning "Space Exploration & Utilisation" activities for the long term (30-year horizon), and implications of weather control will be briefly addressed in that study. Dr. Eastlund's input will be integrated therein. The study results should become available in the March 1999 time frame.

In the meantime, I shall mail to you a copy of Dr. Eastlund's paper, for your information.

Regards,

Mauro Novara
Organiser of EXPLOSPACE Workshop.

---------------------- Forwarded by Gonnie Elfering/estec/ESA on 08-01-99 09:10 AM

**"GRIP - Secteur Recherche" <recherche@grip.org> on 07-01-99 05:04:55 PM**

To: Conference Centre Estec/estec/ESA
cc:
Subject: Explospace 20-22 October 1998

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Dear Sir,

I have heard that Dr Bernard Eastlund (USA) made a statement on "weather modification experiments using high power electromagnetic radiation" during the Explospace Workshop, and that he has a research contract on that subject with the ESA.

However, I do not see his name in the preliminary programme available on your web site.
Can you confirm my information?
In that case, is it possible to get a copy of Dr Eastlund's statement?

I would like to know if ESA is actually conducting research related to weather modification. Could you tell me if there is available public information and wich ESA division I can contact?