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Space options for tropical cyclone hazard mitigation

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ABSTRACT

This paper investigates potential space options for mitigating the impact of tropical cyclones on cities and civilians. Ground-based techniques combined with space-based remote sensing instrumentation are presented together with space-borne concepts employing space solar power technology. Two space-borne mitigation options are considered: atmospheric warming based on microwave irradiation and laser-induced cloud seeding based on laser power transfer. Finally technology roadmaps dedicated to the space-borne options are presented, including a detailed discussion on the technological viability and technology readiness level of our proposed systems. Based on these assessments, the space-borne cyclone mitigation options presented in this paper may be established in a quarter of a century.

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1. Introduction

Tropical cyclones are powerful storm systems that are fueled by the thermal energy stored in warm ocean waters. Strong sustained winds pushing on the ocean surface can give rise to storm surge and hence significant floods, potentially leading to fatalities and property damage. The 2005 and 2012 tropical cyclone seasons were particularly devastating in the North Atlantic Basin following an ongoing era of high hurricane activity [1,2]. Hurricanes Katrina and Sandy, which hit the Louisiana and New Jersey coasts of the United States, are reported to have caused more than 1800 and 120 fatalities, respectively, together with overall losses exceeding $US 135 billion and $US 50 billion, respectively [3,4].

In Japan, the most financially devastating tropical cyclone was Tropical cyclone Bess, which was responsible for more than $US 5.9 billion in damage in 1982 [5]. Over the past 10 years, several large tropical cyclones with damage costs higher than $US 1 billion occurred in Japan, causing flooding in large areas of standing water. According to the Ministry of Land, Infrastructure, Transport and Tourism Japan (MLIT), the average cost due to flooding from 1999 to 2008 was $US 6 million per year and the number of casualties per year exceeded 640 [6].

While considered traditionally as acts of fate and out of reach of human influence, researchers have started considering possible methods to weaken tropical cyclones to mitigate future catastrophic impacts of tropical cyclones on cities and civilians [7–15]. First attempts to mitigate tropical cyclone hazards occurred in the framework of Project Stormfury, where hurricane seeding experiments were conducted in the United States from 1962 to 1983, injecting silver iodine particles using aircrafts to reduce cyclone wind speeds by targeting the cyclone's internal dynamics [7]. Other concepts were later proposed, such as marine cloud brightening, offshore wind turbines, ocean up-welling, and microwave energy transfer. Numerical simulations of tropical cyclone intensity reduction have been performed and ground-based technical concepts devised [8,9,11–15]. To complement these works,

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this paper investigates potential space contributions to currently conceived tropical cyclone hazard mitigation concepts.

Satellites already offer the most convenient method to monitor tropical cyclone development in real-time. A wealth of high-resolution data of tropical cyclone development has been gathered by Earth observation satellites; however their potential for natural disaster prevention might not be fully exploited. In addition to remote sensing applications, space in principle also offers options for a more active role including reducing the threat posed by such developing storm systems. This paper investigates space options to mitigate the impact of tropical cyclones on cities and civilians.

This paper is divided as follows. Section 2 describes the mechanisms of tropical cyclone formation and dissipation. Section 3 presents an overview of ground-based methods and means for threat reduction together with possible space contributions including remote sensing instrumentation. Section 4 presents space-based concepts for tropical cyclone hazard mitigation. Two different mechanisms are considered here: atmospheric heating based on microwave irradiation and laser-induced cloud seeding based on laser power transfer. Technology roadmaps for cyclone mitigation based on two space platform types will be introduced. To improve the tropical cyclone hazard mitigation efficiency a high-accuracy and high-resolution forecast system would be needed, described as the Earth Meteorological Forecast System in section 4. Section 5 concludes with recommendations for further research steps.

2. Mechanisms of tropical cyclone formation and dissipation

2.1. Tropical cyclone formation

Tropical cyclones are massive cyclonic storm systems powered by the release of latent heat during condensation. Low-latitude seas continuously provide the heat and moisture needed for storms to develop. As warm, humid air rises above the sea surface, it cools and condenses to form clouds and precipitation. Condensation releases latent heat to the atmosphere and warms the surrounding air, adding instability to the air mass and causing air to ascend still further in the developing thundercloud. With more moisture and latent heat released this process can intensify to create a tropical disturbance, gathering thunderclouds in a cluster over warm ocean waters. At this stage cyclonic circulation can develop via the Coriolis effect due to Earth's rotation, fueling additional warm, humid air to the storm's core, increasing precipitation rates and latent heat release. This can allow a low-pressure core to develop, increasing further the convergence of warm air towards the center of the disturbance, strengthening the depression as it becomes a tropical storm. This positive feedback process can combine with the increased evaporation at the sea surface due to the strong winds until a distinctive eye and spiral pattern develop. At this stage the storm becomes a typhoon in the Northwest Pacific basin and a hurricane in the Eastern North Pacific and North Atlantic basins with sustained winds of at least 119 km/h. The current understanding of tropical cyclones is reviewed in [16].

2.2. Tropical cyclone dissipation

Tropical cyclone formation and dissipation are governed by the following physical mechanisms:

- *Energy exchange at air–sea interface*: Tropical cyclones are fueled by warm moist air evaporating from the sea surface, hence natural or anthropogenic decreases of sea surface temperature values will very likely cause dissipation within a cyclone. In addition when tropical cyclones make landfall they are deprived of their energy source (i.e. latent heat from warm ocean waters) and will quickly weaken. To a lesser extent, the surface roughness of the land increases friction reduces the circulation pattern hence also weakens the storm.
- *Large-scale interactions with the troposphere*: Tropical cyclones feed on latent heat released during condensation. Moist warm air parcels rising in the cyclone will adiabatically expand and cool at the moist adiabatic lapse rate according to several °C per km. An air parcel will continue rising provided its adiabatic lapse rate is higher than the environment lapse rate. In other words the water vapor contained inside the cooling air parcel condenses, releasing latent heat and allowing that air parcel to stay warmer relative to the environment so that it continues its ascension in the unstable atmosphere. Theoretically, a rising air parcel would tend to be impeded by warm tropospheric temperatures, as it would be colder and denser than its surroundings, preventing further intensification of the storm. Measurements of the difference between tropospheric temperatures and SSTs are of primary importance in tropical cyclone intensification theory [17–19].
  Anthropogenic or naturally occurring changes to the tropospheric temperature structure also induce significant wind shear as the latter depends on the horizontal gradient of the temperature field at several vertical levels [19]. Tropical cyclones are vertically stacked structures that strengthen via their symmetrical three-dimensional circulation; adding a wind pattern aloft such as wind speeds increasing with height could disrupt the cyclone's symmetry, impeding the release of latent heat in the structure and therefore reducing the cyclone intensity. See [20,21] for more information on the impact of vertical wind shear on cyclone intensity change.
- *Internal dynamics* (*cloud microphysics and eyewall replacement cycles*): Tropical cyclones gain energy from the large amounts of latent heat released during condensation and precipitation. One could expect that the redistribution of precipitation patterns induced by changing the cloud microphysical properties could redistribute latent heat leading to changes in the cyclone's internal dynamics and circulation patterns. Specifically targeting the convection outside the inner eyewall might rob the latter of its moisture and energy, leading to the formation of an outer eyewall with reduced surface wind speeds.

3. Ground-based options for tropical cyclone hazard mitigation

Several ground-based techniques have been proposed to mitigate the damage of tropical cyclones. In this section,

we review these options and identify possible space contributions. They are summarized in Table 1.

3.1. Concepts description

3.1.1. Hurricane cloud seeding

Hurricane cloud seeding experiments aim at enhancing precipitation outside the eye wall to disrupt the cyclone's internal dynamics. During Project Stormfury, hurricanes were seeded with silver iodine particles using aircrafts to enhance precipitation outside the eye wall. The silver iodine particles would serve as artificial nuclei for the formation of ice from supercooled water vapor and would precipitate as snow outside the eyewall, locally increasing convection through the release of the latent heat of freezing from supercooled water vapor [22]. This would lead to a reformation of the eyewall at a larger radius, thus decreasing wind speeds through partial conservation of angular momentum [7]. However observations performed later showed that contrary to earlier beliefs tropical cyclones already contain large amounts of ice and very little super-cooled water vapor. These hurricane seeding experiments ceased in 1983.

Project Stormfury aimed at increasing convection outside the eye wall through the release of the latent heat of freezing from supercooled water vapor. To increase the amount of supercooled water available for freezing, other authors have suggested loading a tropical cyclone with large amounts of sub-micron hygroscopic aerosol particles known as cloud condensation nuclei (CCN) to partially suppress the very effective raindrop formation [11,12,23]. More water droplets would reach the 0 °C isotherm level and beyond, increasing the release of the latent heat of freezing in the outer parts of the storm. As in the Stormfury experiment, this would lead to the reformation of the eye wall at a larger radius, eventually leading to its dissipation. Typical CCN densities of 1000 cm^{-3} were considered in the simulations compared to the natural background of 100 cm^{-3} [11,12].

3.1.2. Marine cloud brightening

Marine stratocumulus clouds are low-level clouds that form along the western coasts of continents and cover approximately one quarter of the ocean surface [24]. Their albedo typically ranges from 0.3 to 0.7 and can therefore reflect large amounts of incident solar radiation back to space, leading to cooler surface temperatures. To further increase the albedo of these clouds, seawater droplets with a mean diameter of 0.3 to 0.8 μm may be injected into these clouds, a concept known as marine cloud brightening. In this particular cloud seeding technique these submicron aerosols act as condensation nuclei for small water droplets to form onto, enhancing the cloud reflectivity by increasing the total effective surface area. The cloud lifetime is also possibly enhanced due to a reduction in precipitation rates [24,25].

Marine cloud brightening (MCB) has been suggested by Latham et al. (2012) as a possible technique to decrease SSTs in hurricane forming regions [14], by seeding remote marine stratocumulus clouds as to modify the distribution of heat in the climate system. Simulations of the local negative radiative forcing averaged over the North Atlantic hurricane season using global climate models indicate that MCB might significantly reduce SSTs in hurricane development regions during their genesis and early development [14]. To inject the seawater droplets into the atmosphere, Salter et al. proposed an engineering implementation based on spray systems mounted on unmanned wind-powered sea-going vessels [26].

3.1.3. Offshore wind turbines

Recently offshore wind turbines have been proposed as a simple mechanism to extract kinetic energy from cyclone winds with the aim of reducing wind speeds and storm surge. Numerical simulations of the impact of offshore wind turbines on cyclone surface wind speeds have been performed using a coupled climate–weather forecast model that accounts for the kinetic energy extracted by the turbine rotors. Results showed that large turbine arrays with 300 GW electricity capacity may decrease surface wind speeds by 25–41 ms^{-1} and storm surge by 6–79% [15]. The turbines could decrease the outer rotational winds by extracting kinetic energy, reducing the wave heights at these locations and decreasing surface friction. As the latter weakens the convergence of surface winds at the eyewall, the convection in the eyewall decreases and the central pressure increases, leading to a weaker cyclone. Simulations were conducted for hurricane Sandy, Katrina, and Isaac and the turbines were assumed to be installed offshore in front of major cities and along key coastal areas.

A simple cost–benefit analysis of this concept revealed that the net cost of offshore turbine arrays might be less than that of today's electricity generation from fossil fuels in key coastal areas, taking into account operation costs, electricity generation and costs related to health, climate, and damage avoidance [15].

Table 1
Tropical cyclone hazard mitigation concepts.

Concept	Ground/space[a]	Physical process
Hurricane cloud seeding	G	Internal dynamics
Marine cloud brightening	G	Energy exchange at air–sea interface
Offshore wind turbines	G	Energy exchange at air–sea interface
Compressible free jets	G	Energy exchange at air–sea interface
Ocean upwelling	G	Energy exchange at air–sea interface
Microwave energy transfer	S	Large-scale interactions with the troposphere
Laser-induced condensation	S	Internal dynamics

[a] Applicability: ground-based (G) or space-based (S) concept.

3.1.4. Ocean upwelling

Artificial ocean upwelling is a geoengineering technique aiming at bringing cool, nutrient-rich deep-sea water to the ocean surface using an array of floating pipes [27]. The pipes may be several hundred meters long to allow mixing of surface waters with deep cool waters (typically 11 °C at 315 m depths). Each pipe is attached to a surface buoy at the top and a one-way valve is installed at the bottom. The ocean waves force the valve to open in a wave trough and close at the next wave crest, generating upward movement of cold water through the pipe [28]. Field experiments of wave-driven upwelling pumps have demonstrated pumping rates of 45 m^3 per hour using 300 m-long wave pumps and local SST reduction of more than 1 °C for a duration of 15 h [29].

Artificial ocean upwelling has been suggested as another mean to weaken tropical cyclones by deploying an array of wave-driven upwelling pumps in front of an advancing cyclone. Assuming a deployment time of 12–24 h and knowing in advance the path of the storm, Klima et al. calculated that this technique could lower SSTs by 0.5–1 °C, leading to a decrease in cyclone wind speeds of 15% for a 2 h period spent in the altered SST area [13].

3.1.5. Compressible free jets

A free jet flow is an unbounded flow of one fluid into another fluid due to the pressure difference at the nozzle of a jet engine. The free jet flow is considered compressible when the exhaust velocity is comparable to the sound velocity in the ambient fluid. Compressible free jets are typically turbulent and can transport energy and momentum to the surrounding field [30]. They might be used to weaken hurricanes by inducing large unstable updrafts of humid air from the ocean surface [31]. In this concept multiple jet engines mounted on sea-going vessels introduce intense atmospheric perturbations prior to an advancing cyclone and extract enthalpy (heat) from the ocean surface, decreasing local SSTs. The advancing hurricane would then be partly deprived of its source of energy and would thus weaken. Whether this hurricane modification technique would be effective is unknown at this point [31].

3.2. Potential contributions from space

Space-based platforms help to better understand tropical cyclone development and can be used for tropical cyclone hazard mitigation by providing a synoptic and frequent monitoring of remote areas where tropical cyclones develop. They could also provide a means to discriminate between the effect of human intervention and that resulting from the natural development of cyclones. The Dvorak technique is a well-established empirical tool based on cloud feature recognition to estimate tropical cyclone intensities using satellite-derived data [32,33]. To complement this technique, recent works aiming at integrating newer remote sensing products have yielded promising results for potential tropical cyclone intensity estimation. Such sensors include cloud profiling radars (e.g. CloudSat mission) and imaging spectroradiometers such as the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua platform, both satellites being part of NASA's convoy of A-Train satellites and sharing same orbital characteristics. Combined together, they provide accurate estimates of cloud top pressure and temperature of tropical cyclone eyewalls to estimate tropical cyclone intensities [34].

Orbiting radiometers can also be used to estimate surface wind speeds by measuring changes in brightness temperature. Designed to measure soil moisture and ocean salinity (SMOS), ESA's Earth Explorer SMOS mission can provide reliable estimates of cyclone surface wind speeds under stormy, rainy conditions. The MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) instrument onboard the SMOS satellite operates at 1.4 GHz in the L-band and measures brightness temperature, i.e. microwave radiation, which can be affected by oceanic whitecaps – those long white patches of foam that arises in stormy conditions [35–38]. With its 1200-km swath width, 3-day subcycle and average spatial resolution of 50 km, SMOS offers opportunities to complement the Dvorak technique and standard aircraft dropsonde data [37].

Active options to measure cyclone wind speeds include making use of their distorting effect on reflected signals from Global Positioning Systems (GPS) or active synthetic aperture radar (SAR) data via an increase in small-scale ocean roughness. Wind speeds retrieved via SAR imagery have been shown to agree well with dropsonde data and with an accuracy comparable to microwave radiometer data (error ~4 m/s in C-band), while offering the benefit of higher spatial resolution [38,39]. Moreover wind speeds in excess of 40 m/s could be retrieved via GPS signals (in L-band) with 5–8 m/s accuracy [40,41]. Planned for launch within the next few years is the CYGNSS (Cyclone Global Navigation Satellite System) mission from NASA consisting of eight microsatellites designed to measure cyclone surface wind speeds by detecting direct and reflected GPS signals. The complete constellation will provide gap-free coverage of Earth's surface with a 4-h revisit time over the tropics [42].

In addition to monitoring surface wind speeds and tropical cyclone intensity, space instruments could provide additional useful information. For instance cloud profiling radars could help to assess the impact of cloud seeding. The main issue with the experimental verification of precipitation-enhancement experiments lies in the high level of noise present in naturally precipitating clouds. In particular difficulties arise in tracking the seeding particles over the target area and to relate changes in liquid water content and ice particle size distribution to anthropogenic seeding activity [43]. Cloud-profiling radars, space-borne backscatter lidars and imaging radiometers can be used in synergy to accurately retrieve the vertical distribution of cloud microphysical properties such as liquid water content, ice water content and ice particle size [43,44]. As for the marine cloud brightening concept, the wind-powered sea-going vessels used for injecting submicron seawater droplets could be remotely controlled from space to allow the unmanned fleet to follow suitable cloud fields. Finally for the offshore wind turbines, the compressible free jets and ocean upwelling techniques, the space contribution would mostly be restricted to the passive monitoring role described above.

4. Space-based options for tropical cyclone hazard mitigation

This section proposes space-based concepts based on space platforms for tropical cyclone threat reduction. They are summarized in Table 1.

4.1. Cyclone threat reduction via space-based microwave energy transfer

As described in Section 2.1, one of the causes for cloud formation is the cooling of humid air. The concept presented in this section therefore proposes a heat irradiation system to modify the cloud formation and cyclone development. Energy would be deposited via microwaves to slightly warm the humid air from a space-based solar power station (SPS) in a dual use mode [45].

The accurate transmission of thermal energy to tropical cyclones via microwaves requires highly accurate pointing and forecast accuracy regarding the storm's position and path. Details are presented below.

4.1.1. Heat irradiation system

The functions of this system consist of (i) generating power with solar energy, (ii) converting electric power to a radio frequency to alter the tropical cyclone development, and (iii) heat irradiation to the tropical cyclone from space. Such technologies are studied in the frame of space solar power station concepts and would thus strongly benefit from developments in this field. Three key technologies would need to be developed: transmission, beam pointing, and frequency switching. The viability of these technologies is described in the next subsection. To locally heat regions of the atmosphere effectively, a frequency of 183 GHz is chosen, which is located within a strong absorption band of water vapor, the main component of a tropical cyclone.

In addition, high-accuracy pointing technology is needed to irradiate energy to the tropical cyclone. We assume that (i) the rev method and (ii) the amplitude monopulse method, which have been studied as part of the Japanese work on space solar power concepts, are applicable. A schematic view of these methods is shown in Fig. 1. In the rev method, we set the transmitter on the transmission panel (Fig. 1, left) and calibrate the phase by using the signal from a pilot transmitter (Fig. 1, right). In the amplitude monopulse method, a pilot transmitter and a receiver are set on the rectenna and the transmission panel, respectively, and we detect the arrival direction from the pilot signal.

With these energy transmission and beam-pointing systems, we estimate the irradiation time needed to influence the tropical cyclone development. Simulation results from Hoffman (2004) indicate that a temperature increase of nearly 2 °C causes the route modification or the reduction of the tropical cyclone [47]. Under the following assumptions: (i) a transmission power is 1.5 GW with one space platform, (ii) the target is only water vapor, and the absorption rate of the power is 100%, (iii) the density of the water vapor is 5 g/m^3 [48], and (iv) the irradiation area has a circular, cylindrical shape with a 100-km diameter and 10-km height, heating a tropical cyclone by 2 °C with an irradiation duration of 5 d by five SPSs. Heat irradiation for only a 100 km scale area could be effective for tropical cyclone hazard mitigation with the assumption that the irradiation is done during the early development of the tropical cyclone. Under these assumptions such a system could actively influence tropical cyclone development. Heat irradiation from space has the advantage of instantaneousness and regional/global operability as compared to a ground-based hazard mitigation system. More detailed system-level studies and more considerations on the size and dynamics of the irradiation area are needed to mature the concept.

An interesting aspect of the concept lies in its potential to act as a dual use system, generating electricity at remote locations during most of its operational time when not used as a heat irradiation system. To transmit power to Earth during normal operations, a 6-GHz transmission frequency is assumed, while the heat irradiation system requires a transmission frequency of 183 GHz. Such a system requires as a critical technology an efficient frequency switching mechanism between 183 GHz and 6 GHz. Fig. 2 shows the operation image of the heat irradiation system.

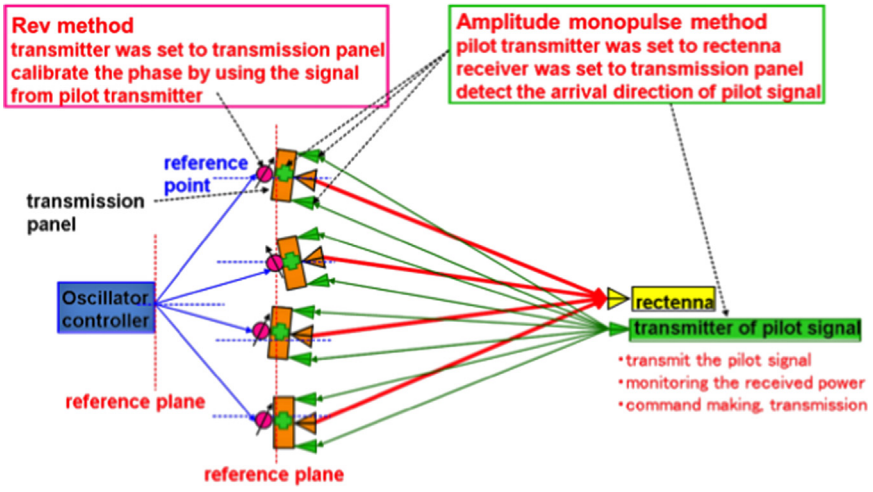

Fig. 1. Schematic view of the beam-pointing technology (adapted from [46]).

The transmitting antenna is assumed to be shared between the two frequencies. Local oscillator and high power amplifier would be prepared individually.

4.1.2. Technological viability

To evaluate the technological viability of the proposed system, we identified its key technological challenges and their Technology Readiness Level (TRL). Then we set an R&D plan to raise the TRL of each key technology based on its present value (see Table 2).

We assume that the technology which has been developed by the JAXA SPS R&D team will be used as much as possible. Specific technology development areas for the hazard mitigation system are the high frequency transmission and the frequency switching system. The 183-GHz transmission system could benefit from technological advancements obtained during the development of the 94-GHz transmission system for the joint JAXA-ESA EarthCare mission [49]. Technical difficulties include low noise countermeasure for the transmission system and antenna development for the frequency switching system. Finally further research activities are needed to improve the antenna gain and mirror accuracy (on the order of 1/50f, where f is the frequency) for the frequency transmission system. Fig. 3 shows the technology roadmap for the development of the proposed system within a 25-year time frame.

4.2. Cyclone threat reduction via space-based laser energy transfer

Here we suggest a novel tropical cyclone hazard mitigation concept based on femtosecond laser filamentation and space-based laser energy transfer. In this technique, femtosecond terawatt-scale laser pulses propagate in the atmosphere in a self-focused beam owing to the dynamic competition between the optical Kerr effect focusing the beam and the induced plasma effect defocusing the beam. This results in the formation of thin (100 μm) plasma filaments with typical lengths of several hundred meters and light intensities clamped at around 10^{13} W/cm^2 [50]. Ground-based laser filamentation has been demonstrated recently by propagating terawatt laser pulses in the atmosphere over more than a 20-km distance using a mobile laser and detection system embedded in a standard freight container [51].

4.2.1. Laser-induced condensation

To locally alter precipitation rates aerosol particles can be dispersed in the atmosphere using aircrafts, ground-based dispersion devices such as canisters fired from rockets [12,52] or ground-based generators using orographic lifting [22]. Recently, laser-induced condensation has been demonstrated using intense femtosecond laser pulses in a controlled laboratory environment as well as in outdoor conditions [53,54]. Strong droplet formation was observed over a wide range of diameters (25 nm–10 μm), temperatures (2–36 °C), and relative humidity (35–100%). In particular the density of 25-nm diameter particles increased to 10^5 cm^{-3} close (~2 cm) to the laser filaments using 240-fs laser pulses with a 160-mJ pulse energy compared to the background concentration of less than 10^4 cm^{-3} [54]. The effect was attributed to the very

Table 2
Key technologies and R&D steps.

Key technology	TRL	R&D steps
Earth Meteorological Forecast System		
Earth Observation Satellite	9	N/A
Earth Observation Ground System	9	N/A
Numerical weather model	2	I
Supercomputer	2	I
Total System Assimilation	1	I and II
Heat Irradiation System		
Energy transmission	2	I–III
Beam pointing	3	II and III
Frequency switching	2	I–III

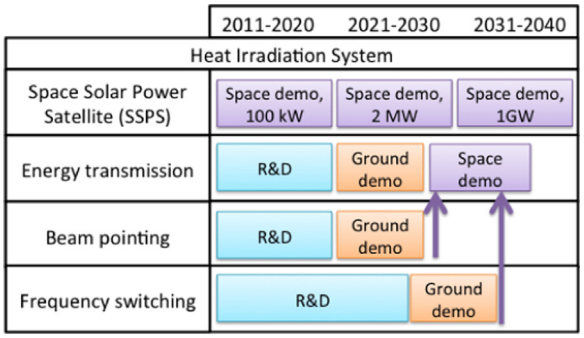

Fig. 3. Technology roadmap for the heat irradiation system based on information provided in [46] for the beam pointing technology and [49] for the frequency transmission system.

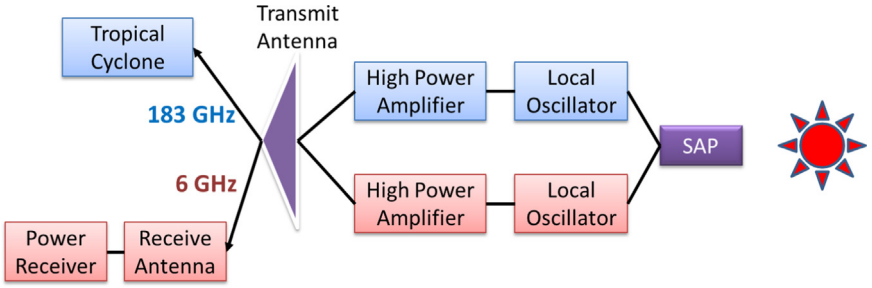

Fig. 2. Operation image of the heat irradiation system.

effective atmospheric photochemistry induced by the multiphoton dissociation and ionization of air molecules, creating highly reactive species that lead to the generation of hygroscopic molecules such as HNO_3 which are in turn very efficient at absorbing moisture [54].

Based on these results, laser-induced condensation is suggested here as a possible technique for tropical cyclone threat reduction. The basic principle is to apply intense femtosecond laser pulses to outer cloud bands of a cyclone (see Fig. 4). These would generate large amounts of artificial CCN, i.e. water droplet embryos, which would compete for the available water vapor and thus locally reduce precipitation rates. Intense upward air currents induced by the filaments as in [53] would efficiently advect the water droplets to the 0 °C isotherm and beyond, so that the water droplets release more latent heat of freezing, thus invigorating convection at the cyclone periphery [12]. These thunderclouds would compete with the original eye-wall, creating a wider eye, resulting in a decrease in wind speeds through conservation of angular momentum.

Laser-induced condensation might offer an effective way to remotely alter the tropical cyclone development. Laser filaments propagate with little perturbation through adverse conditions such as clouds and fog via the surrounding energy reservoir replenishing the plasma core [55]. In addition laboratory experiments have demonstrated a highly nonlinear generation of CCN as a function of the laser intensity, potentially offering attractive opportunities for large-scale atmospheric implementation. Although the exact nonlinear contribution could not be determined due to the limited number of experimental data points, the generation of droplet embryos is believed to be scaling between the fifth and eighth power law with respect to incident laser intensity, corresponding to multiphoton dissociation and ionization of oxygen, respectively [56]. Contrary to aerosol injection, laser-induced condensation may be switched off, allowing for a precise control of the injection region. Finally laser-induced condensation relies on molecules already present in the atmosphere, thus by avoiding the introduction of additional chemicals in the atmosphere it would also eliminate some of the secondary effects injections might have.

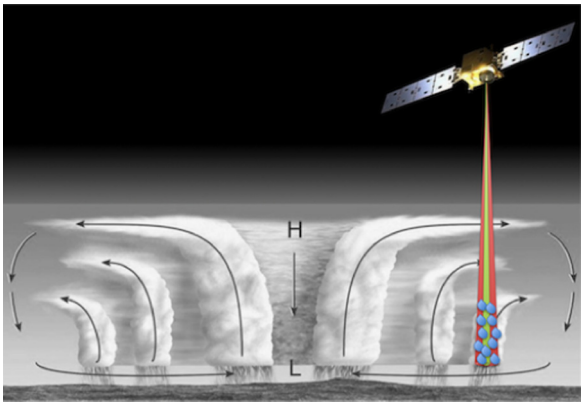

Fig. 4. Artistic representation of the concept of laser-induced condensation for tropical cyclone hazard mitigation (not to scale). The red and green laser beams represent the femtosecond pump beam and nanosecond probe beam, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

4.2.2. Space-based laser-induced cloud seeding system

This active tropical cyclone hazard mitigation concept may be based on the following SPS scheme for global perspective and instant accessibility to remote areas. A large-scale space borne power generation platform, i.e. a laser-based SPS station, would provide the power source required for the laser-induced cloud seeding system, however more consideration is needed to precisely assess the required SPS capacity. The SPS station could be based on the modular electric laser concept as described in [57], comprising a series of numerous individual elements beaming their optical energy towards ground-based photovoltaic (PV) arrays. However instead of beaming their energy towards ground stations, the various optical beams would target specific areas within a cyclone, following cloud coverage data obtained using satellite microwave imagery.

To generate the laser filaments from such distances, a significant frequency chirp would be added to the initial laser pulses thus compensating for group velocity dispersion in the atmosphere, which would spread the laser pulses in the time domain and correspondingly decrease its peak power due to conservation of energy. The laser chirp would be set so that the laser filaments are generated in the troposphere inside the cyclone. Precise pointing of the femtosecond beam would allow the generation of artificial CCN over several kilometers along these narrow light filaments. To induce significant weakening, CCN density levels in the range of 1000–2000 cm^{-3} would be required at the cyclone periphery according to [11,12]. Such CCN density levels might be obtained locally by the laser filamentation process via the nonlinear scaling of the droplet generation with the laser intensity [56]. More in-depth consideration and a better understanding of the scaling laws would be needed to assess the effectivity of the proposed method. Schemes could be devised to obtain the cyclone intensity reduction or to alter its track to avoid hitting high density population areas.

To measure the laser-induced condensation in seeded cyclones, a backscatter space Lidar is proposed here in a pump-probe configuration, where the femtosecond laser pulses act as the pump beam and nanosecond laser pulses collinear with the filaments probe the size distribution and concentration of the artificial CCN generated by the filaments [58]. To evaluate the effectiveness of this technique a Doppler module could be integrated in the Lidar detection system to retrieve cyclone wind speeds. Other options include making use of the distortion effect of small-scale ocean roughness on reflected GPS signals and SAR data as presented in Section 3.2.

4.2.3. Technological viability

The laser-induced cloud-seeding system is based on a space platform, which could in principle be similar to space-based solar power platforms transmitting energy via laser beams. Compared to other transmission systems, these have relatively small-size components due to the latter scaling with optical wavelengths. A modular, self-

assembling space infrastructure would keep the *Cost to First Power* relatively low. Key technologies to be developed would be the following: high-accuracy beam pointing technology to target specific areas within a cyclone, high-efficiency solar power generation via multi-bandgap PV cells, and an effective thermal management system to dissipate any significant waste heat generated by the laser systems. Fig. 5 shows a potential schematic technology roadmap for a laser-induced cloud seeding system, which could be established in a quarter of a century. The associated current technology readiness levels (TRLs) are shown in Table 3.

As a first implementation of the laser-induced cloud seeding system in orbit, a single femtosecond laser system based on the analogy to the tested terrestrial system described in [59] would require the high but technically already achievable power level of 30 kW in orbit. More consideration regarding the irradiation area and needed pulsed laser intensities would determine more precisely the electric power requirements. One important technological issue regarding the high-power laser system is that it should operate under an extended temperature range and harsh radiation environment. Research is currently under way to develop space-qualified ultrashort-pulse terawatt lasers [60].

Finally applied research on laser filamentation is already well under way, with a ground-based prototype already demonstrated in environmental conditions [54]. Recent works have shown a strong relationship between the laser parameters required for the filamentation process

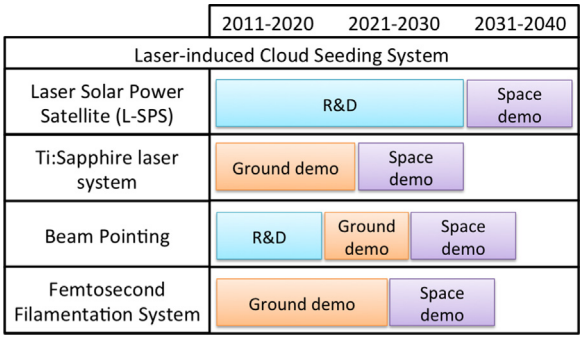

Fig. 5. Technology roadmap for the laser-induced cloud seeding system based on information provided in [57] for the L-SPS platform and beam pointing system and [59,60] for the laser filamentation system.

Table 3
Technology readiness levels (TRLs) for the laser-induced cloud seeding system.

Key technology	TRL
Laser Solar Power Satellite (L-SPS)	3
Ti:Sapphire laser system	6
Beam Pointing	5
Femtosecond Filamentation System	6

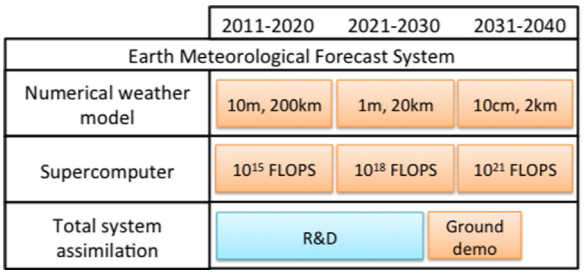

Fig. 6. Technology roadmap for the Earth Meteorological Forecast System, including accuracy requirements for the numerical weather model at 500 h Pa altitude and the cyclone path as well as supercomputing performance requirements.

and the atmospheric conditions along the propagation path. This highlights the need for a better understanding of the impact of atmospheric turbulence and upper-atmospheric cold plasma conditions on the filamentation process to adjust the laser parameters. Any practical implementation of a laser filamentation system in space would require a continuous research commitment to obtain a detailed understanding of the underlying physics principles in order to reduce the risk and uncertainty associated with such a system, including a detailed evaluation of the impact of any active interference of such extreme weather phenomena on the climate system in order to avoid negative unforeseen consequences.

4.3. *Earth Meteorological Forecast System*

The Earth Meteorological Forecast System (EMFS) is a high resolution forecast system that will be needed for simulating tropical cyclone development in synergy with mitigation techniques. The requirements for the EMFS are the following: (i) high prediction accuracy for the global forecast numerical weather model, which is 10 cm or better at 500 h Pa altitude and 10 km or better for the cyclone's track, and (ii) computing performance exceeding 10^{21} floating-point operations per second (FLOPS) to resolve the tropical cyclone in simulation and compare with real-time observations. High accuracy of the EMFS is needed for the regular total system assimilation to correct for bias errors of both observed data and simulated predicted data. Such higher simulation accuracy for the forecast system will be enabled via data acquired by Earth system missions such as JAXA's Global Change Observation Mission [61], which targets essential variables of the atmosphere, ocean, land, cryosphere, and ecosystem, to improve the efficacy of tropical cyclone hazard mitigation concepts. The technology roadmap for the EMFS is presented in Fig. 6. The EMFS will consist of the Earth and Ground Observation System Families and the Meteorological Forecast System; we assume that it will be applied within the Global Earth Observation System of Systems (GEOSS), the open-access Earth Observation integration system.

5. Concluding remarks

Potential space contributions to the following tropical cyclone hazard mitigation concepts have been presented in this paper: hurricane cloud seeding, marine cloud

brightening, offshore wind turbines, compressible free jets, ocean up-welling, microwave energy transfer, and laser-induced cloud seeding. These different techniques either target the energy exchange at the air-sea interface, large-scale interactions with the troposphere or the cyclone internal dynamics via modifications of the cloud microphysical properties with the objective of dissipating cyclones or altering their path to mitigate their impact on cities and civilians.

It can be anticipated that field tests might be conducted to evaluate the effectiveness of such mitigation concepts. One key challenge will be to distinguish changes in the cyclone's state due to anthropogenic perturbations from changes due to the natural development of the storm system. In this respect, space-based sensors could provide valuable remote-sensing data. Perhaps the most interesting cyclone hazard mitigation concepts from the point of view of space applications are microwave energy transfer to induce temperature perturbations at different atmospheric depths and laser-induced cloud seeding to alter the cyclone's internal dynamics by targeting the outer cloud walls using orbiting laser-emitting stations.

Even though the large-scale human and material losses associated with such extreme weather phenomena might justify attempting their mitigation, any active interference would require a thorough evaluation of their impact on the climate system. Tropical cyclones provide a natural mechanism for removing large amounts of thermal energy stored in ocean waters and impact local water and wind resources via their large precipitation rates and high wind speeds; any large-scale systematic mitigation approach would therefore disrupt the thermal, hydrological and wind cycles associated with cyclones. Political and legal concerns would also need to be taken into account and potential consequences considered carefully, in addition to the mechanisms for threat reduction being well understood and their efficacy well proven. Such scheme would therefore need to be conducted under proper regulatory framework and oversight.

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References

[1] K. Emanuel, Increasing destructiveness of tropical cyclones over the past 30 years, Nature 436 (7051) (2005) 686–688.
[2] P.J. Webster, G.J. Holland, J.A. Curry, H.-R. Chang, Changes in tropical cyclone number, duration, and intensity in a warming environment, Science 309 (5742) (2005) 1844–1846.
[3] R. Enz, A. Zanetti, T. Hess, Natural Catastrophes and Man-made Disasters 2005: High Earthquake Casualties, New Dimension in Windstorm Losses, National Emergency Training Center, Emmitsburg, MD, 2006.
[4] J. Strachan, J. Camp, Tropical cyclones of 2012, Weather 68 (5) (2013) 122–125.
[5] A. Kitamoto, Digital typhoon: near real-time aggregation, recombination and delivery of typhoon-related information (cd–rom), in: Fourth International Symposium on Digital Earth, 2005.
[6] MLIT, Damage Cost Caused by Flooding in 2008, Press Release, 2008.
[7] H. Willoughby, D. Jorgensen, R. Black, S. Rosenthal, Project stormfury: a scientific chronicle 1962–1983, Bull. Am. Meteorol. Soc. 66 (5) (1985) 505–514.
[8] R.N. Hoffman, Controlling the global weather, Bull. Am. Meteorol. Soc. 83 (2) (2002).
[9] J.M. Henderson, R.N. Hoffman, S.M. Leidner, T. Nehrkorn, C. Grassotti, A 4D-Var study on the potential of weather control and exigent weather forecasting, Q. J. R. Meteorol. Soc. 131 (612) (2005) 3037–3051.
[10] M. Alamaro, J. Michele, V. Pudov, A preliminary assessment of inducing anthropogenic tropical cyclones using compressible free jets and the potential for hurricane mitigation, J. Weather Modif. 38 (2006) 82–96.
[11] W.R. Cotton, H. Zhang, G.M. McFarquhar, S.M. Saleeby, Should we consider polluting hurricanes to reduce their intensity, J. Weather Modif. 39 (2007) 70–73.
[12] D. Rosenfeld, A. Khain, B. Lynn, W. Woodley, Simulation of hurricane response to suppression of warm rain by sub-micron aerosols, Atmos. Chem. Phys. 7 (13) (2007) 3411–3424.
[13] K. Klima, M.G. Morgan, I. Grossmann, K. Emanuel, Does it make sense to modify tropical cyclones? A decision-analytic assessment, Environ. Sci. Technol. 45 (10) (2011) 4242–4248.
[14] J. Latham, B. Parkes, A. Gadian, S. Salter, Weakening of hurricanes via marine cloud brightening (MCB), Atmos. Sci. Lett. 13 (4) (2012) 231–237.
[15] M.Z. Jacobson, C.L. Archer, W. Kempton, Taming hurricanes with arrays of offshore wind turbines, Nat. Clim. Change 4 (3) (2014) 195–200.
[16] Y. Wang, C.-C. Wu, Current understanding of tropical cyclone structure and intensity changes—a review, Meteorol. Atmos. Phys. 87 (4) (2004) 257–278.
[17] K.A. Emanuel, An air-sea interaction theory for tropical cyclones. Part i: steady-state maintenance, J. Atmos. Sci. 43 (6) (1986) 585–605.
[18] W. Shen, R.E. Tuleya, I. Ginis, A sensitivity study of the thermodynamic environment on GFDL model hurricane intensity: implications for global warming, J. Clim. 13 (1) (2000) 109–121.
[19] B.H. Tang, J.D. Neelin, ENSO influence on Atlantic hurricanes via tropospheric warming, Geophys. Res. Lett. 31 (24) (2004) L24204.
[20] M. DeMaria, The effect of vertical shear on tropical cyclone intensity change, J. Atmos. Sci. 53 (14) (1996) 2076–2088.
[21] W.M. Frank, E.A. Ritchie, Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes, Mon. Weather Rev. 129 (9) (2001) 2249–2269.
[22] D. Breed, R. Rasmussen, C. Weeks, B. Boe, T. Deshler, Evaluating winter orographic cloud seeding: design of the Wyoming weather modification pilot project (wwmpp), J. Appl. Meteorol. Climatol. 53 (2) (2013) 282–299.
[23] Y. Wang, K.-H. Lee, Y. Lin, M. Levy, R. Zhang, Distinct effects of anthropogenic aerosols on tropical cyclones, Nat. Clim. Change 4 (5) (2014) 368–373.
[24] R. Wood, Stratocumulus clouds, Mon. Weather Rev. 140 (8) (2012) 2373–2423.
[25] A.-I. Partanen, H. Kokkola, S. Romakkaniemi, V.-M. Kerminen, K.E. Lehtinen, T. Bergman, A. Arola, H. Korhonen, Direct and indirect effects of sea spray geoengineering and the role of injected particle size, J. Geophys. Res.: Atmos. 117 (D2) (2012) D02203.
[26] S. Salter, G. Sortino, J. Latham, Sea-going hardware for the cloud albedo method of reversing global warming, Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 366 (1882) (2008) 3989–4006.
[27] J.D. Isaacs, D. Castel, G.L. Wick, Utilization of the energy in ocean waves, Ocean Eng. 3 (4) (1976) 175–187.
[28] P.W. Kithil, A device to control sea surface temperature and effects on hurricane intensity, in: 27th Conference on Hurricanes and Tropical Meteorology, 2006, p. 3B.6.
[29] A. White, K. Björkman, E. Grabowski, R. Letelier, S. Poulos, B. Watkins, D. Karl, An open ocean trial of controlled upwelling using wave pump technology, J. Atmos. Ocean. Technol. 27 (2) (2010) 385–396.
[30] P.M. Sforza, R.F. Mons, Mass, momentum, and energy transport in turbulent free jets, Int. J. Heat Mass Transf. 21 (4) (1978) 371–384.
[31] M. Alamaro, J. Michele, V. Pudov, A preliminary assessment of inducing anthropogenic tropical cyclones using compressible free jets and the potential for hurricane mitigation, J. Weather Modif. 38 (2006) 82–96.
[32] V.F. Dvorak, Tropical cyclone intensity analysis and forecasting from satellite imagery, Mon. Weather Rev. 103 (5) (1975) 420–430.

[33] C. Velden, B. Harper, F. Wells, J.L. Beven, R. Zehr, T. Olander, M. Mayfield, C. Guard, M. Lander, R. Edson, et al., The Dvorak tropical cyclone intensity estimation technique: a satellite-based method that has endured for over 30 years, Bull. Am. Meteorol. Soc. 87 (9) (2006) 1195–1210.
[34] S.B. Sieron, F. Zhang, K.A. Emanuel, Feasibility of tropical cyclone intensity estimation using satellite-borne radiometer measurements: an observing system simulation experiment, Geophys. Res. Lett. 40 (19) (2013) 5332–5336.
[35] D.B. Ross, V. Cardone, Observations of oceanic whitecaps and their relation to remote measurements of surface wind speed, J. Geophys. Res. 79 (3) (1974) 444–452.
[36] E.C. Monahan, I.G. O'Muircheartaigh, Whitecaps and the passive remote sensing of the ocean surface, Int. J. Remote Sens. 7 (5) (1986) 627–642.
[37] N. Reul, J. Tenerelli, B. Chapron, D. Vandemark, Y. Quilfen, Y. Kerr, Smos satellite l-band radiometer: a new capability for ocean surface remote sensing in hurricanes, J. Geophys. Res.: Oceans 117 (C2) (2012) C02006.
[38] E.W. Uhlhorn, P.G. Black, J.L. Franklin, M. Goodberlet, J. Carswell, A.S. Goldstein, Hurricane surface wind measurements from an operational stepped frequency microwave radiometer, Mon. Weather Rev. 135 (9) (2007) 3070–3085.
[39] J. Horstmann, C. Wackerman, S. Falchetti, S. Maresca, Tropical cyclone winds retrieved from synthetic aperture radar, Oceanography 26 (2) (2013) 46–57.
[40] S.J. Katzberg, O. Torres, G. Ganoe, Calibration of reflected gps for tropical storm wind speed retrievals, Geophys. Res. Lett. 33 (18) (2006) L18602.
[41] S.J. Katzberg, J. Dunion, G.G. Ganoe, The use of reflected gps signals to retrieve ocean surface wind speeds in tropical cyclones, Radio Sci. 48 (4) (2013) 371–387.
[42] C. Ruf, M. Unwin, J. Dickinson, R. Rose, D. Rose, M. Vincent, A. Lyons, Cygnss: enabling the future of hurricane prediction, Geosci. Remote Sens. Mag. 1 (2) (2013) 52–67.
[43] Q. Miao, B. Geerts, Airborne measurements of the impact of ground-based glaciogenic cloud seeding on orographic precipitation, Adv. Atmos. Sci. 30 (4) (2013) 1025–1038.
[44] J. Delanoë, R.J. Hogan, Combined cloudsat-calipso-modis retrievals of the properties of ice clouds, J. Geophys. Res.: Atmos. 115 (D4) (2010) D00H29.
[45] R. Nakamura, Y. Arikawa, T. Itahashi, Active typhoon control with space solar power technology, in: Proceedings of the 63rd International Astronautical Congress, Naples, Italy, vol. 12, 2012, p. C3.1.8.
[46] K. Maki, K. Hashimoto, N. Shinohara, D. Jodoi, et al., Overview of microwave transmission experiment for space solar power system, in: Third Small Scientific Satellite Symposium, Japan, 2013, p. P48.
[47] R.N. Hoffman, Controlling hurricanes, Sci. Am. (October) (2004) 68–75.
[48] Y. Takayama, Research for Observation of Vertical Profile of Water Vapor with Microwave Radiometer (Original in Japanese), Technical Report 06A0970665, Institute of Meteorological research of Japan, 2004.
[49] Y. Aida, E. Tomita, H. Nakatsuka, Y. Seki, K. Okada, G. Kadosaki, Y. Iide, H. Horie, K. Sato, Y. Ohno, et al., Earthcare/cpr design results and pfm performance, in: SPIE Remote Sensing, International Society for Optics and Photonics, 2013, p. 88890A.
[50] A. Couairon, A. Mysyrowicz, Femtosecond filamentation in transparent media, Phys. Rep. 441 (2–4) (2007) 47–189.
[51] M. Rodriguez, R. Bourayou, G. Méjean, J. Kasparian, J. Yu, E. Salmon, A. Scholz, B. Stecklum, J. Eislöffel, U. Laux, A.P. Hatzes, R. Sauerbrey, L. Wöste, J.-P. Wolf, Kilometer-range nonlinear propagation of femtosecond laser pulses, Phys. Rev. E 69 (3) (2004) 036607.
[52] D. Rosenfeld, W.L. Woodley, A. Khain, W.R. Cotton, G. Carrió, I. Ginis, J.H. Golden, Aerosol effects on microstructure and intensity of tropical cyclones, Bull. Am. Meteorol. Soc. 93 (7) (2012) 987–1001.
[53] J. Ju, J. Liu, C. Wang, H. Sun, W. Wang, X. Ge, C. Li, S.L. Chin, R. Li, Z. Xu, Laser-filamentation-induced condensation and snow formation in a cloud chamber, Opt. Lett. 37 (7) (2012) 1214–1216.
[54] S. Henin, Y. Petit, P. Rohwetter, K. Stelmaszczyk, Z. Hao, W. Nakaema, A. Vogel, T. Pohl, F. Schneider, J. Kasparian, K. Weber, L. Wöste, J.-P. Wolf, Field measurements suggest the mechanism of laser-assisted water condensation, Nat Commun. 2 (2011) 456.
[55] G. Méjean, J. Kasparian, J. Yu, E. Salmon, S. Frey, J.-P. Wolf, S. Skupin, A. Vinçotte, R. Nuter, S. Champeaux, et al., Multifilamentation transmission through fog, Phys. Rev. E 72 (2) (2005) 026611.
[56] M. Petrarca, S. Henin, K. Stelmaszczyk, S. Bock, S. Kraft, U. Schramm, C. Vaneph, A. Vogel, J. Kasparian, R. Sauerbrey, K. Weber, L. Wöste, J.-P. Wolf, Multijoule scaling of laser-induced condensation in air, Appl. Phys. Lett. 99 (14) (2011) 141103.
[57] J.C. Mankins, Space Solar Power the First International Assessment of Space Solar Power: Opportunities, Issues and Potential Pathways Forward, International Academy of Astronautics, Paris, 2011, 272p.
[58] J. Kasparian, J.-P. Wolf, Ultrafast laser spectroscopy and control of atmospheric aerosols, Phys. Chem. Chem. Phys. 14 (26) (2012) 9291–9300.
[59] H. Wille, M. Rodriguez, J. Kasparian, D. Mondelain, J. Yu, A. Mysyrowicz, R. Sauerbrey, J.P. Wolf, L. Wöste, Teramobile: a mobile femtosecond-terawatt laser and detection system, Eur. Phys. J.—Appl. Phys. 20 (03) (2002) 183–190.
[60] W.T. Lotshaw, Emerging Technologies: Ultrashort-Pulse Lasers for Space Applications, Technical Report 1, The Aerospace Corporation, Spring 2011.
[61] K. Imaoka, M. Kachi, H. Fujii, H. Murakami, M. Hori, A. Ono, T. Igarashi, K. Nakagawa, T. Oki, Y. Honda, et al., Global change observation mission (gcom) for monitoring carbon, water cycles, and climate change, Proc. IEEE 98(5) (2010) 717–734.