Wireless Power Transmission and Space

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Outline

Why space … and why not

WPT Application Areas in and for space

Context - ESA and ESA’s Advanced Concepts Team

Technical Solutions - an overview

Technical Activities

Wireless Power Transmission - an old dream

Physics basis

- 1873: Maxwell predicts energy transport via electromagnetic waves through vacuum
- 1885-89: Hertz validates Maxwell's predictions

Attempts to deliver electrical power without wires since late 1800s

- Nikola Tesla experimented with transmitting power with a goal of a worldwide wireless power distribution system.
- From 1899 to 1901, Tesla carried out WPT experiments in Colorado Springs, and then Long Island Sound (Wardenclyffe Tower Facility)
- Tesla thought his invention's capability for power transmission was even more important than its abilities as a method for communications

Wireless Power Transmission – far field

- World-war II: availability of high power microwave beams
- 1950s/60s: semiconductors
- Pioneering work by B. Brown at Raytheon during 1960s/70s
  - 1963, transmission of of 400 Watt showed to US Air Force at Raython's converted by a receiving antenna into 100 W of dc power to drive a motor attached to a fan.
  - November 1964, 10h continuous, wireless powered helicopter flight, based on a newly developed rectenna for the receiving part, generating up to 270W.
  - September 1970, the first overall efficiency measurement: 26% dc to dc efficiency
  - 1975, overall system efficiency was increased to 54% with a total power output of 495W.
- 1968: P. Glaser: first engineering concept for SPS published in Science
- 1975: first large-scale, long-distance experiment by Raython under JPL contract at the Venus Site of the JPL Goldstone Facility: 1.6km, >30 kW of dc power. Part of dc output was used to light light-bulbs.
- 1980s/90s/00s: N. Kaya (JP): airplane, balloon, space-craft WPT experiments Canadian and Japanese experiments to power airplanes, balloons, etc and study ionospheric interactions during 1980s
- 1996: Retrodirective system
- Furoshiki experiment demonstrating retro-directive system in 2006 from space to ground
- First successful end-to-end system demonstrations at Hawaii in 2009 and 2010 (N. Kaya, J. Mankins)

WPT:

Why space? … any why not

Why space? … and why not

Space = high inherent risks = conservative

- taking risks where these are <u>necessary</u> to achieve missions objectives, but avoiding all other additional risks
- "space qualified" and proven in past missions are convincing arguments against introduction of alternatives

Why space? … and why not

Space = Stringent Requirements

- Very high standards
- Very stringent requirements

Why space? ... and why not

Space = Integrated, Interdependent and Optimised

- mass as cost driver leads to very high integration levels
- high integration levels result in strong interdependencies expressed in “interface requirements”

Why space? … and why not

Space = Cutting Edge, State-of-the-Art, Pushing the boundaries of what is possible

- Every new mission and application pushes the boundaries of what is technically achievable
- Challenging user needs (scientists, commercial and governmental customers) are driving space engineers to develop new solutions, new technologies, new concepts

Why space? … and why not

Space = Talents, Ingenuity, Inventiveness, Curiosity

- selective recruitment process and highly specialised education and experiences
- passions for advanced technologies
- “geeky”

Why space? … and why not

Open questions:

Can space be a lead market for WPT?, and if yes,

What type of wireless power transmission for what applications?

or

Will space be a potential beneficiary of wireless power transmission technologies developed for other sectors?

Why space? … and why not

Space = mass optimisation

- Mass equals to cost for space missions
- harness accounts for as much as 10% of the dry mass of spacecraft
- 25% for power cables
- 55% for cabling between sensors and actuators; of which over 90% to simple sensors and actuators

Satellite	Dry mass (kg)	Harness mass (kg / %)	
Goce	740	60	8.1%
Cluster-2	540	33.4	6.2%
Mars Express	450	28	6.2%
Smart-I	280	22.1	7.9%
Proba	100	7.6	7.6%
Envisat	8500	850	10.0%

WPT application areas in and for space

WPT application areas in and for space

Offer unique solutions

- what concepts and solutions WPT can offer that are impossible or impractical with current solutions?

Offer non-critical solutions

- introduction of WPT into non-mission critical aspects

Offer solutions for future, longer-term needs

- future space concepts offer still long-enough development and maturation times to introduce new technologies such as WPT

WPT application areas in and for space

Unique solutions

- replacement of moving parts (e.g. slip ring connector joints)
- power delivery to physically disconnected elements (sensors, spacecraft in swarms)
- power delivery to very fast moving elements
- exploration of dark areas
- …

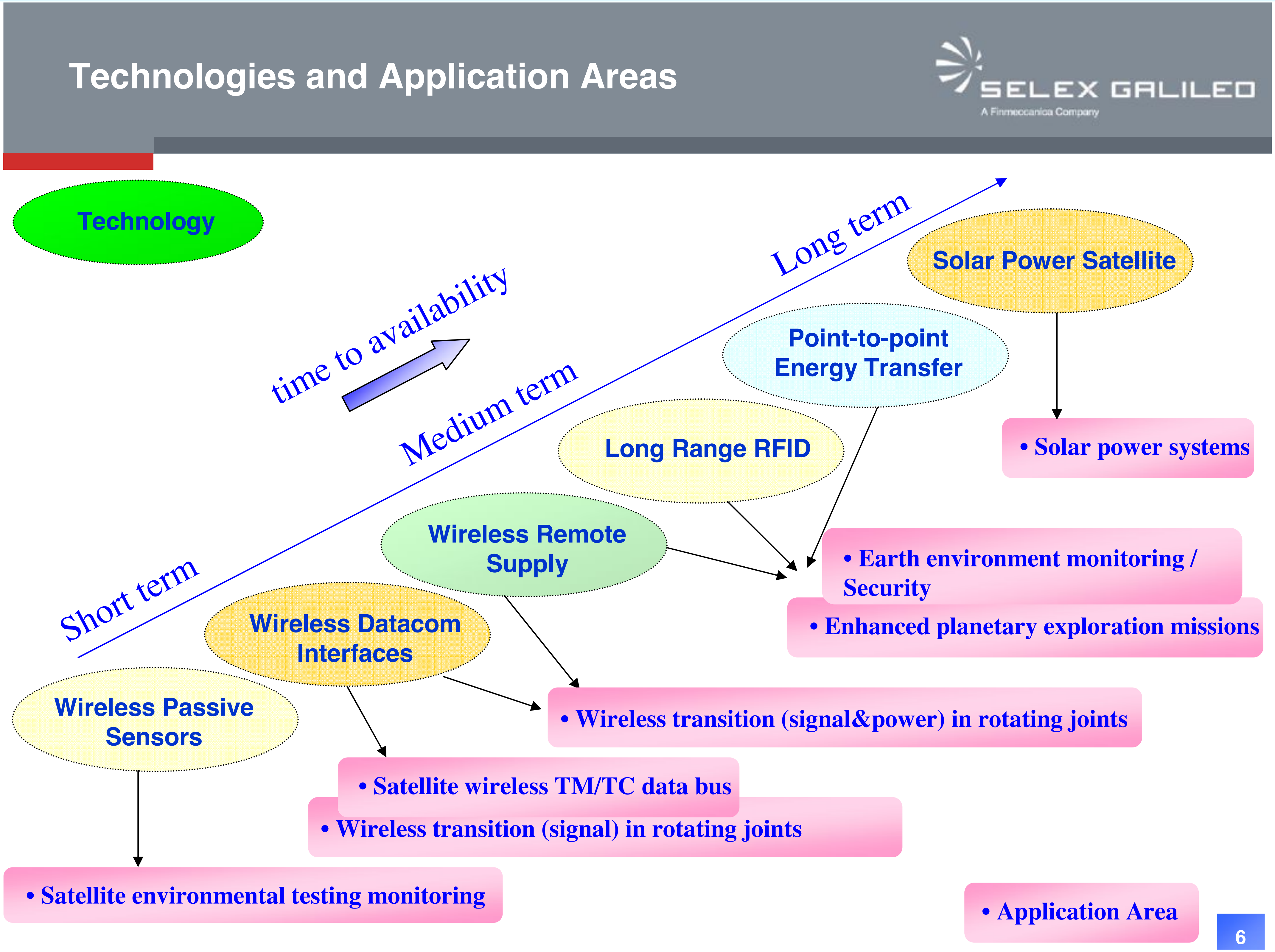
Non-critical solutions

- ground segment solutions
- test centres
- non-critical sensors
- …

Solutions to future, longer-term needs

- fractionated spacecraft
- very large swarms of s/c
- space elevators
- solar power satellites
- …

Space Industry Perspective (example)

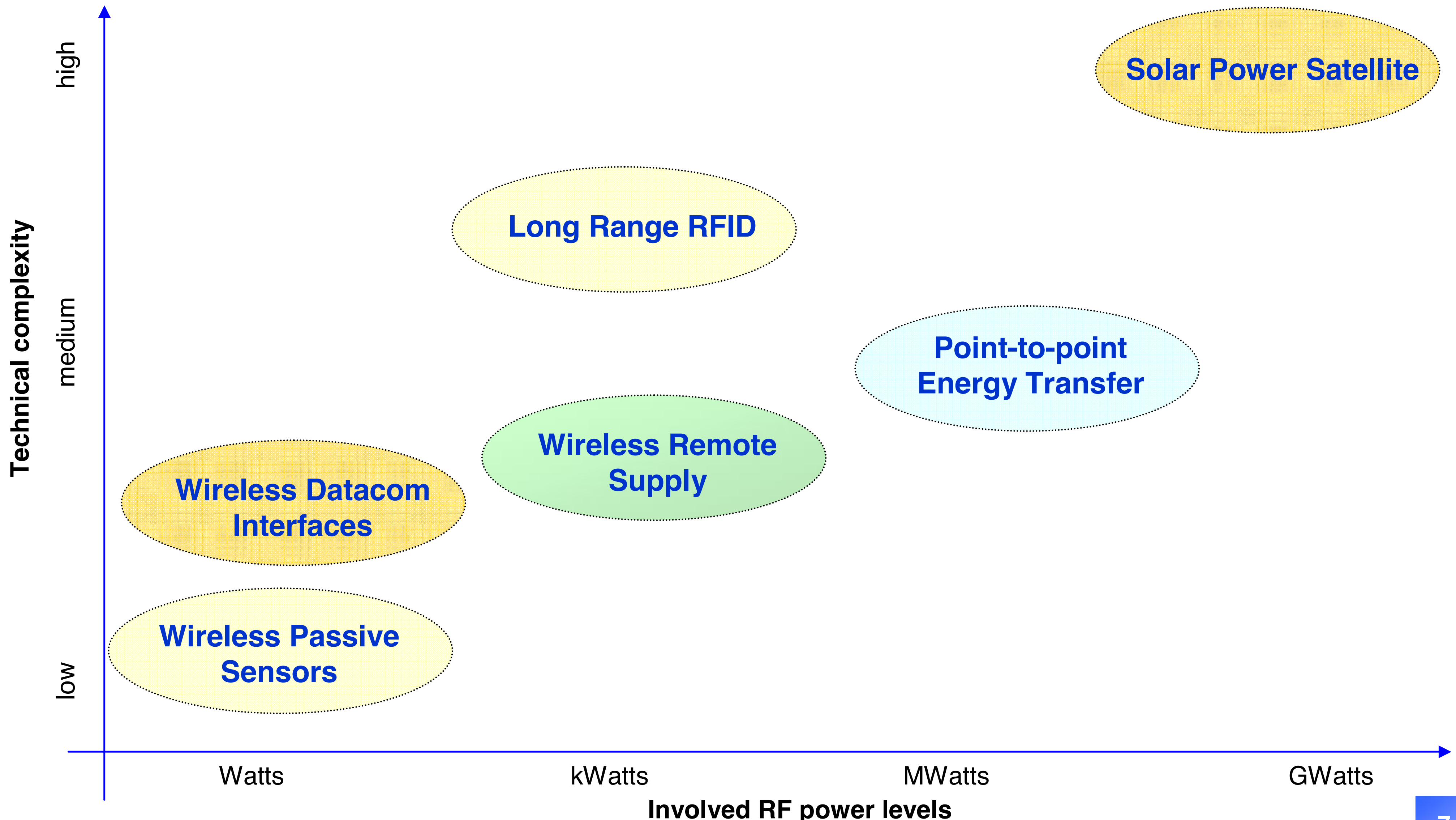


Space Industry Perspective (example)

Technologies perspective

SELEX GALILEO
A Finmeccanica Company

Estimate of technical feasibility



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Context
- European Space Agency
- ESA's Advanced Concepts Team

PURPOSE OF ESA

"To provide for and promote, for exclusively peaceful purposes, cooperation among European states in **space research** and **technology** and their **space applications.**"

Article 2 of ESA Convention

ESA FACTS AND FIGURES

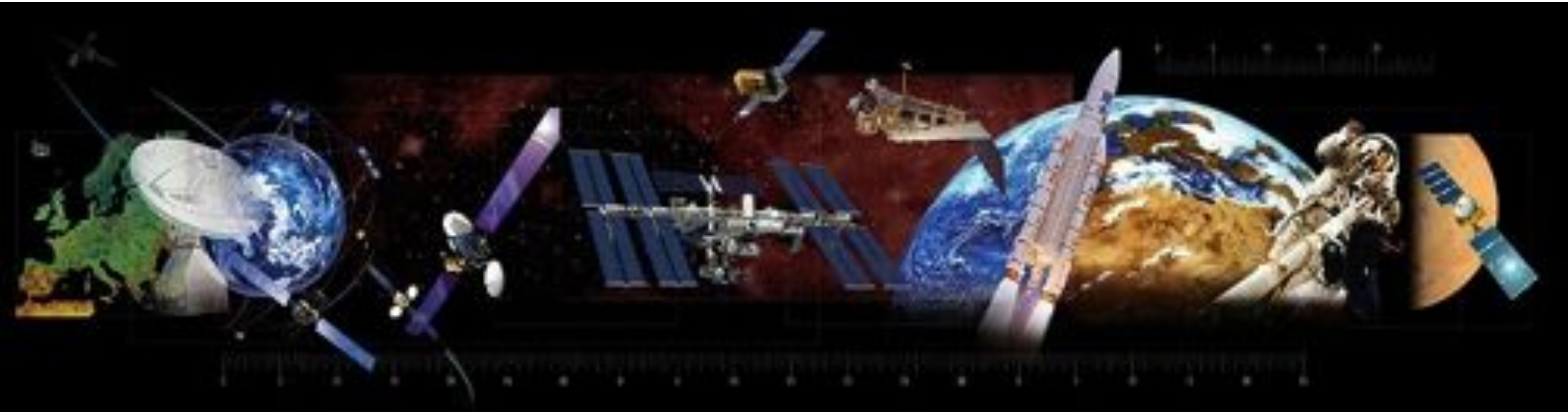
- Over 50 years of experience
- 20 Member States
- Eight sites/facilities in Europe, about 2200 staff
- 4.1 billion Euro budget (2014)
- Over 70 satellites designed, tested and operated in flight
- 18 scientific satellites in operation
- Six types of launcher developed
- 200th launch of Ariane celebrated in February 2011

ACTIVITIES

ESA is one of the few space agencies in the world to combine responsibility in nearly all areas of space activity.

- **Space science**
- **Human spaceflight**
- **Exploration**
- **Earth observation**
- **Launchers**
- **Navigation**
- **Telecommunications**
- **Technology**
- **Operations**

* Space science is a **Mandatory programme**, all Member States contribute to it according to GNP.
All other programmes are **Optional,** funded 'a la carte' by Participating States.



20 MEMBER STATES AND GROWING

ESA has 20 Member States: 18 states of the EU (AT, BE, CZ, DE, DK, ES, FI, FR, IT, GR, IE, LU, NL, PT, PL, RO, SE, UK) plus Norway and Switzerland.

Eight other EU states have Cooperation Agreements with ESA: Estonia, Slovenia, Hungary, Cyprus, Latvia, Lithuania, Malta and the Slovak Republic. Bulgaria is negotiating a Cooperation Agreement. Discussions are ongoing with Croatia.

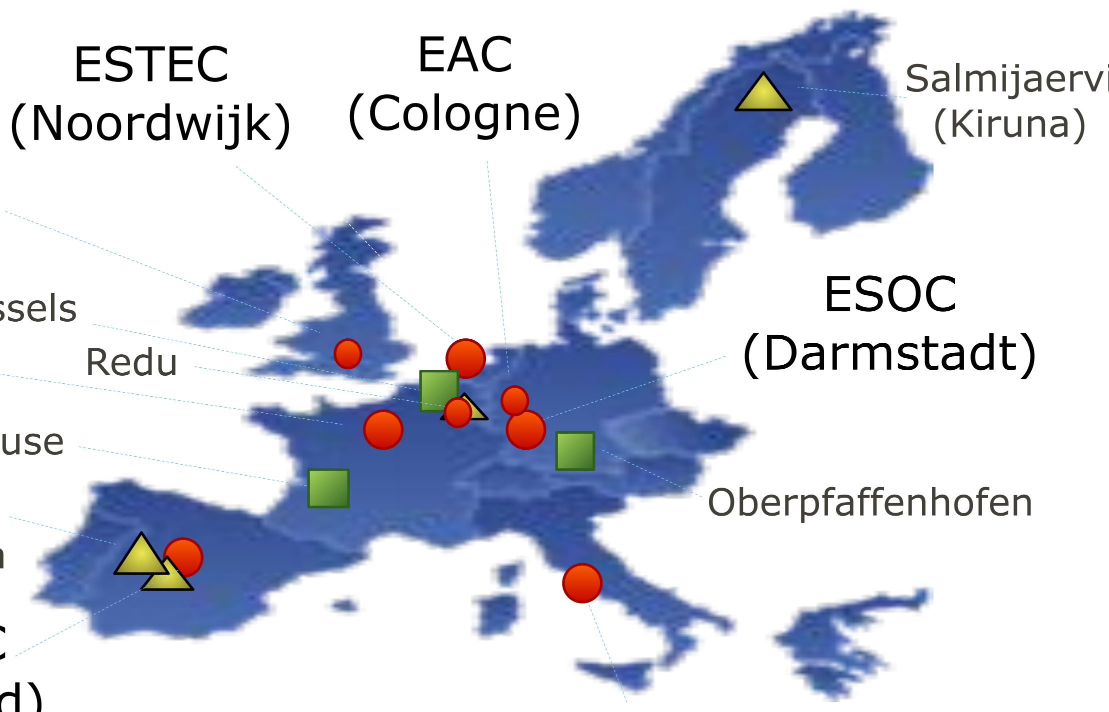
Canada takes part in some programmes under a long-standing Cooperation Agreement.

ESA'S LOCATIONS

ESA sites/facilities

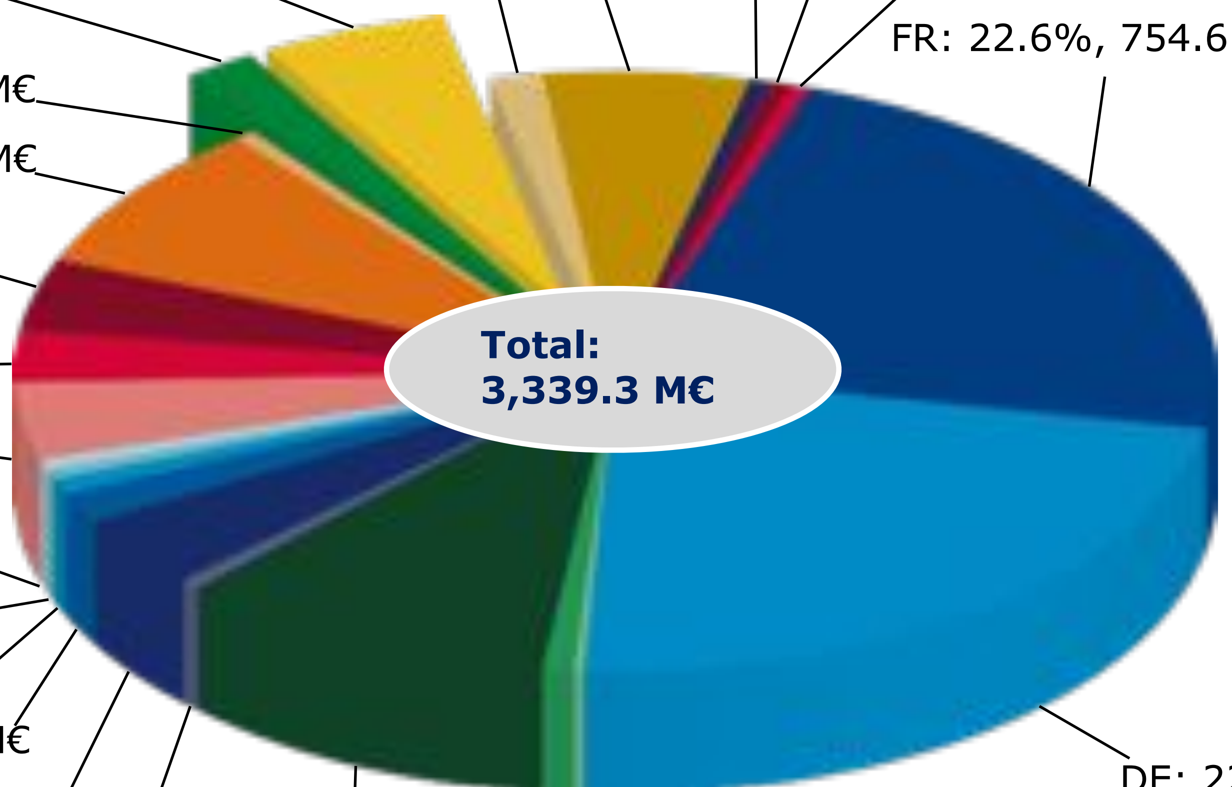
Offices

ESA ground stations

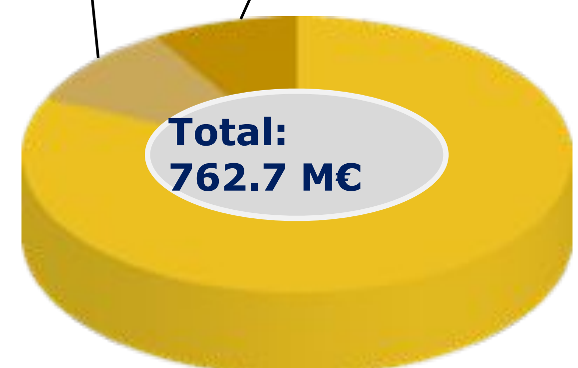


ESA BUDGET FOR 2014

ESA Activities and Programmes

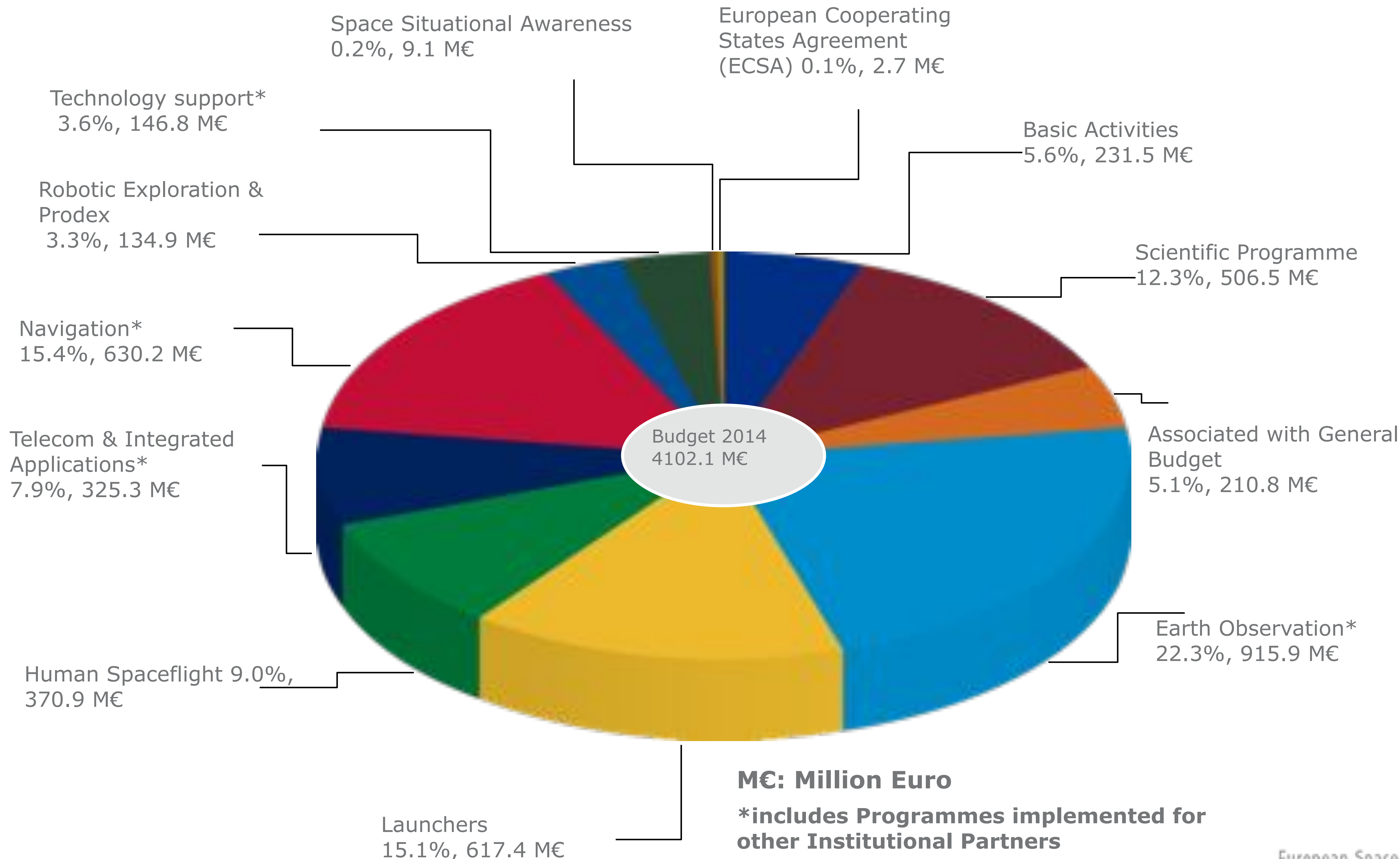


Programmes implemented for other Institutional Partners



TOTAL ESA BUDGET FOR 2014: 4102.1 M€

ESA 2014 BUDGET BY DOMAIN



M€: Million Euro

***includes Programmes implemented for other Institutional Partners**

ESA's Advanced Concepts Team

created in 2002

- based on temporary researchers

Origins and Goals

- "monitor, perform and foster research on advanced space systems, innovative concepts and working methods"

Results

- early identification of trends and topics, provision of solid expertise on advanced research topics, working link to non-space academia, scientific reputation, >450 publications, copied/regarded as model

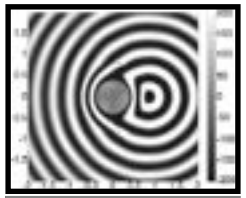
Purpose



concepts, techniques & scientific domains with **no/weak links to space**

biomimetic approaches to engineering, brain-machine interfaces, liquid breathing, curiosity cloning, peer-to-peer computing, crowd sourcing gaming, innovation diffusion and dynamics



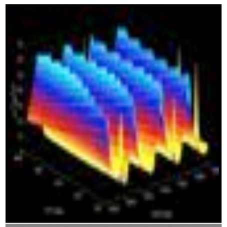
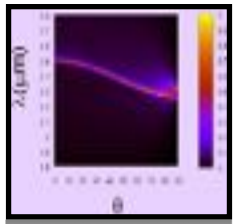


too **immature** for regular ESA programmes or projects

planetary protection research, space nuclear power sources, asteroid deflection, liquid ventilation, pulsar navigation,

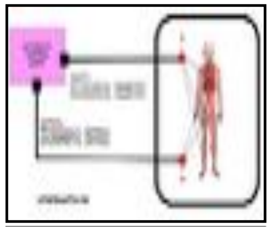
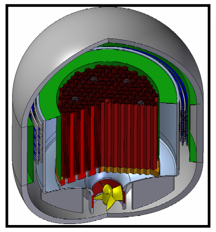
monitor, **perform** and **foster** research on advanced space systems, innovative concepts and working methods

emerging from cutting-edge **basic scientific research**

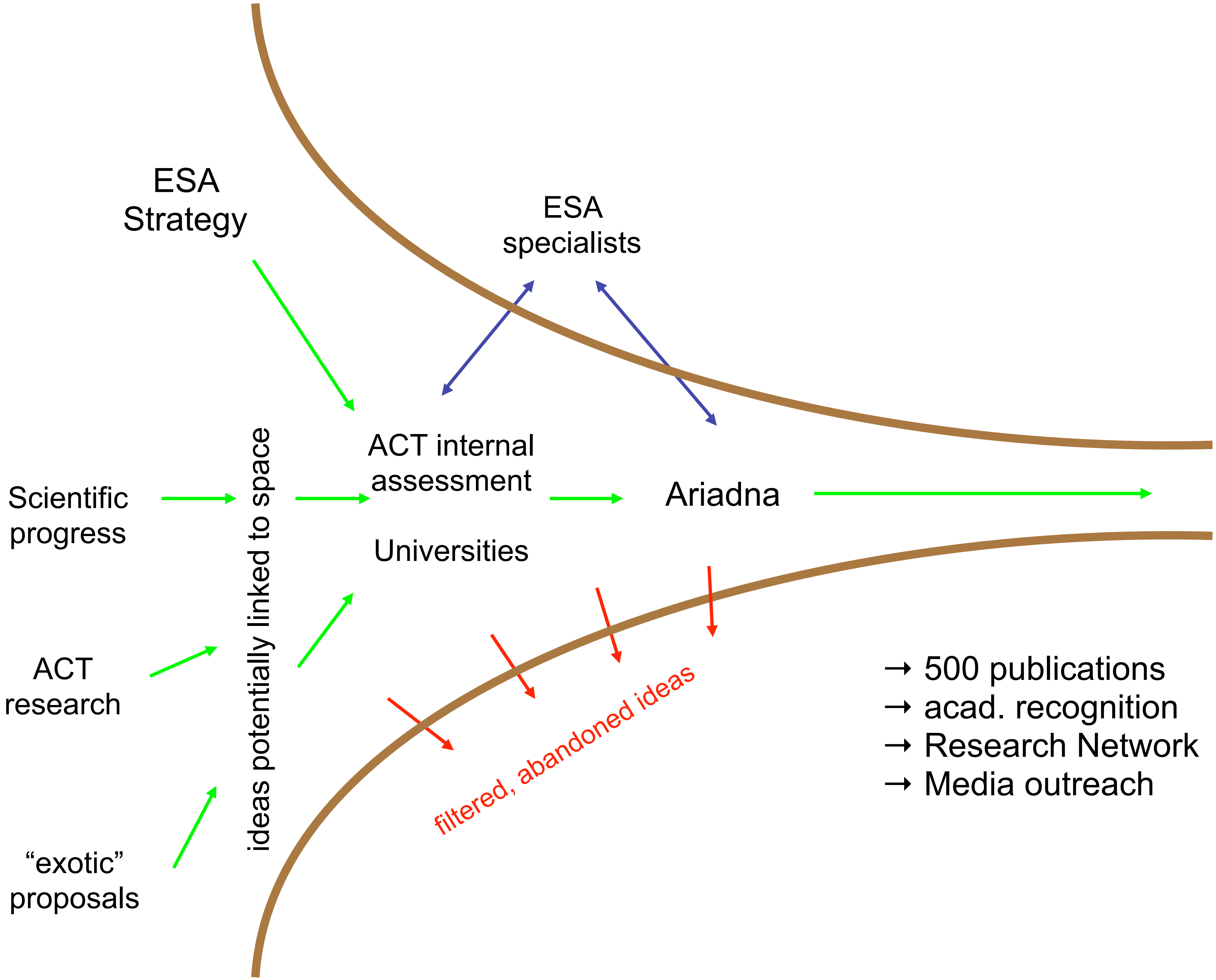

mathematical global optimisation techniques, cloud-based uncertainty modelling, helicon thrusters, pure general relativistic approach to GNSS constellation design, vibrating systems in general relativity, metamaterials in the optical frequency range, distributed/swarm intelligence

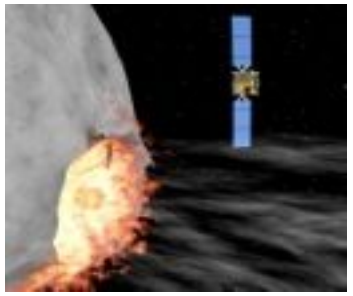
topics on which ESA is **expected to have a position**

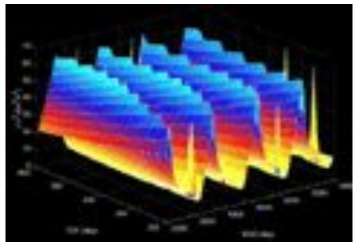




solar power from space, use of hypo-metabolic states for space travel ("hibernation"), asteroid deflection, active removal of space debris, novel working methods based on new IT tools like virtual collaborative environments, terraforming and geoengineering

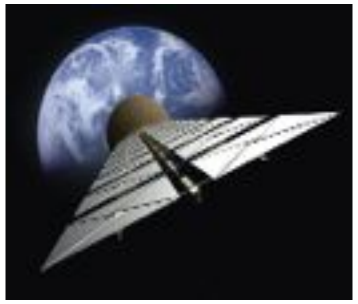
Bridge to new trends and ideas







Positions - Strategies
Knowledge - Networks
Concepts



Technical Solutions - an overview

Far field - microwave

- \+ large distances
- \+ good efficiency
- \- line of sight needed
- \- interferences
- \- safety
- \- e-m compatibilities

Far field - laser

- \+ very large distances
- \+ decent efficiency
- \- line of sight needed
- \- interferences
- \- safety
- \- dual-use potential
- \- maturity

Near/mid field - magnetic/RF

- \- short distances
- \+ very good efficiencies
- \+ passes obstacles
- \+ little interferences
- \+ safety

WPT Applications - examples

A. Wireless passive sensors for monitoring systems

- ESA Study in the frame of the Innovation Triangle Initiative based on surface acoustic waves
- Proposed by Selex ES, Politecnico Milano, Thales Alenia Space
- ESA Contact Point: Jean-Francois Dufour

B. Wireless Power transmission and fractionated spacecraft

- Conceptual and research work
- Extending the near field
- ESA ACT research contact: Thijs Versloot

C. Future, long distance power transmission concepts

- conceptual and research work
- Earth-to-space, space-to-space, space-to-Earth WPT
- ESA ACT research contact: Thijs Versloot, Isabelle Dicaire

Wireless passive sensors for monitoring systems

Objectives

- Reduce AIT costs for temperature monitoring on space platforms during on-ground environmental tests
- Improve installation flexibility and reduce payload mass

Problem Description

- Huge quantity of temperature sensors installed in a medium size satellite, more than 500 copper-constantan thermocouples
- All sensors wired to the acquisition system via hermetic feed through (TVAC facility limit)
- Complexity of harnesses and assembly process

Investigated Solution

- Replace part of conventional wired thermocouples with wireless instrumentation
- Use of RF based systems relying on surface acoustic waves (SAW) passive sensors for temperature remote monitoring

Source: SELEX ES, PoliMI, TAS, ESA ITI

Wireless passive sensors for monitoring systems

Potential Benefits

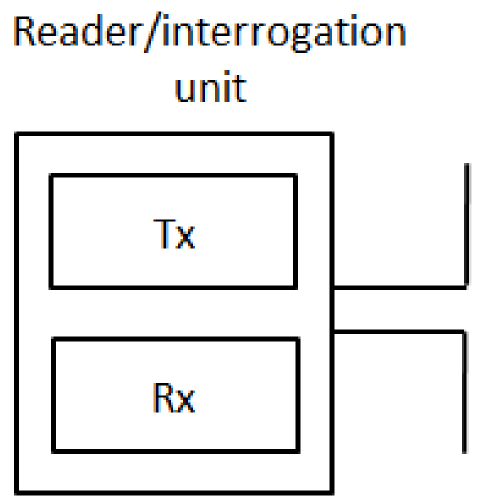
- No wires: reduction of harnesses complexity, leading to shorter integration times and reduced payload mass
- No batteries and no active circuits, simple piezoelectric device, no maintenance, robustness and reliability
- Wide temperature range and insensitivity to ionising radiation
- Flexibility in modifying an already installed configuration (adding of a sensor)
- Ideally suited where access is limited or restricted and where providing power supply to sensors is difficult (with respect to active sensors)
- Removal of wire bundles and slip-rings of rotating joints

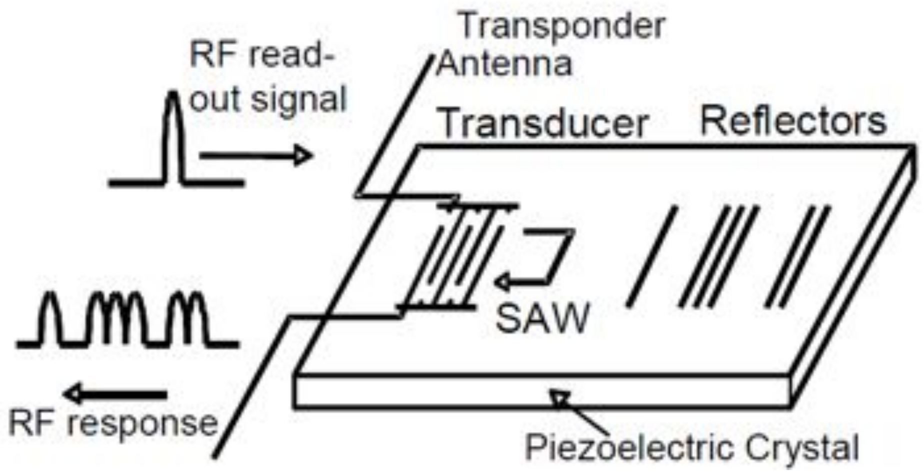
Source: SELEX ES, PoliMI, TAS, ESA ITI

Wireless passive sensors for monitoring systems

Interrogation techniques with SAW sensors

- System composed of a reader and a number of sensors
- Completely passive sensors: a substrate of piezoelectric material (Quartz or LiNbO3)
- Technical complexity moved to the reader unit: peculiar RF interrogation signal
- Two functions: identification and sensing -> SAW tagged-sensor
- Anti-collision function: capability to identify and distinguish the sensors responses
- Multiple access techniques for anti-collision: FDMA, TDMA, CDMA and combinations
- Spectral efficiency intended as number of sensors per unit bandwidth ≈ 1÷3 MHz per sensor
- From commercial market: systems developed only with FDMA like approach, other types seem to be still at laboratory level prototypes





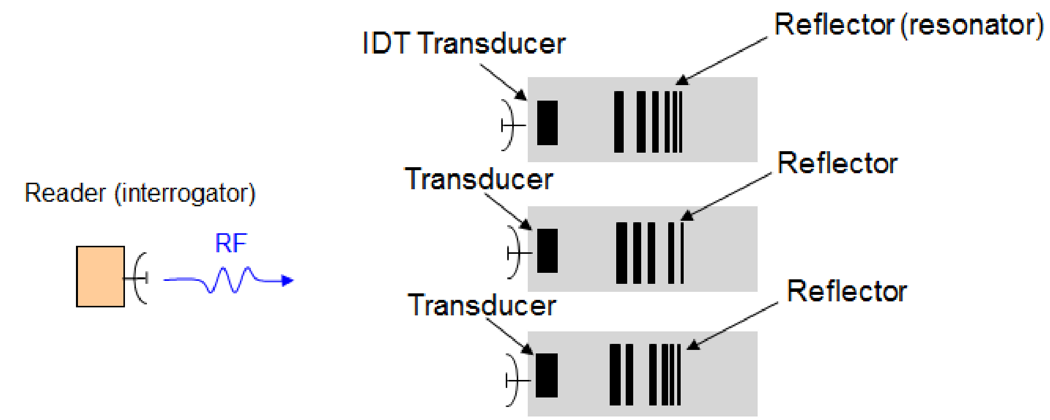
Source: SELEX ES, PoliMI, TAS, ESA ITI

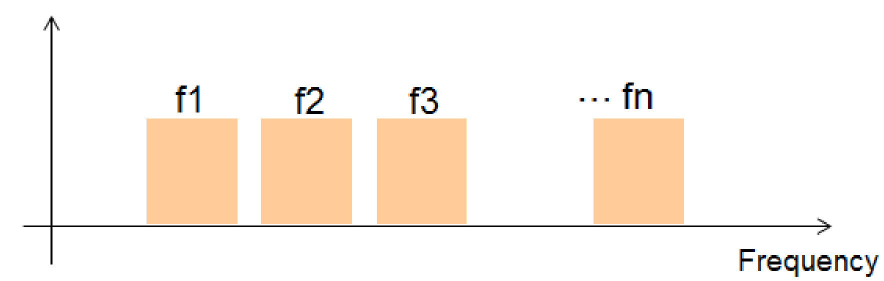
Wireless passive sensors for monitoring systems

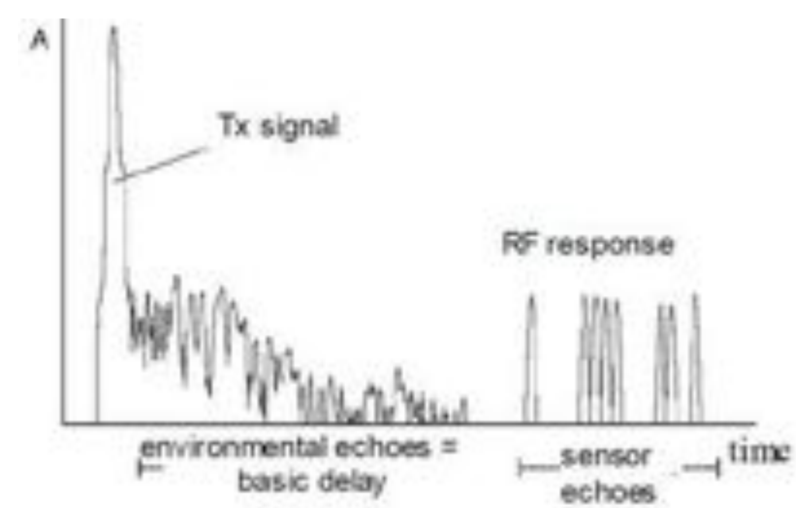
➢ FDMA like interrogation

- Sensor Identification
  - SAW device as a narrow band high Q resonator
  - Orthogonal to each other in frequency, i.e. different frequency bands for each sensor
  - SAW storage time (delay) longer than the duration of the decay of the environmental electromagnetic RF request echoes, 10 μs versus 10 ns over short distances (a few meters)

- Temperature Detection
  - shift of the centre frequency of the resonator with a typical temperature coefficient of ≈ 10 kHz/° C at 430 MHz







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Source: SELEX ES, PoliMI, TAS, ESA ITI

➢ Main wireless system (SENSeOR)

Reader

Interrogation antennas

Wireless
Sensors

Source: SELEX ES, PoliMI, TAS, ESA ITI

Wireless passive sensors for monitoring systems

➢ Auxiliary wireless system (Sengenuity)

- Based on Time Domain Sampling (TDS), pulsed interrogation signal
- Double heterodyne down-conversion is employed in reception with in-phase and quadrature sample streams at baseband
- Low sensitivity to saturation effects in the receiver
- Fixed transmitted power level, adjustable by software interface
- Single resonator design for the sensors
- Single interrogating antenna

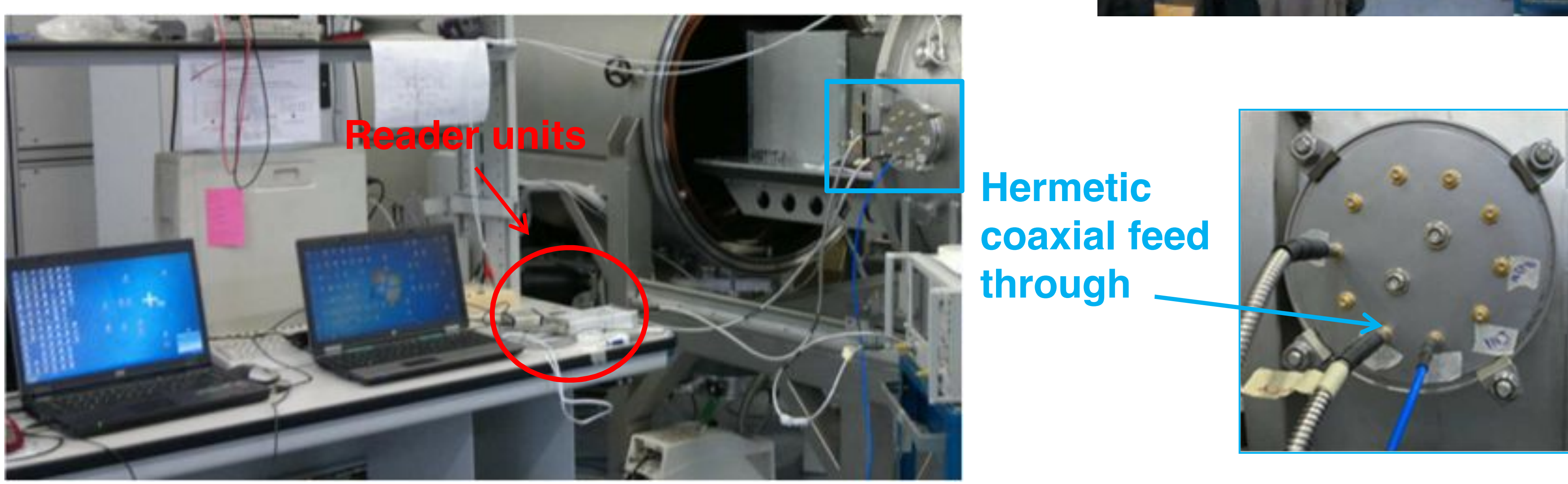
Source: SELEX ES, PoliMI, TAS, ESA ITI

Wireless passive sensors for monitoring systems

esa

➢ Test bed implementation

- Selex ES thermal vacuum chambers test facility
- The reader units of the wireless systems are placed outside the chamber and connected to the internal interrogation antennas via hermetic coaxial feed through
- PC's are used for interfacing the readers



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Source: SELEX ES, PoliMI, TAS, ESA ITI

Wireless passive sensors for monitoring systems

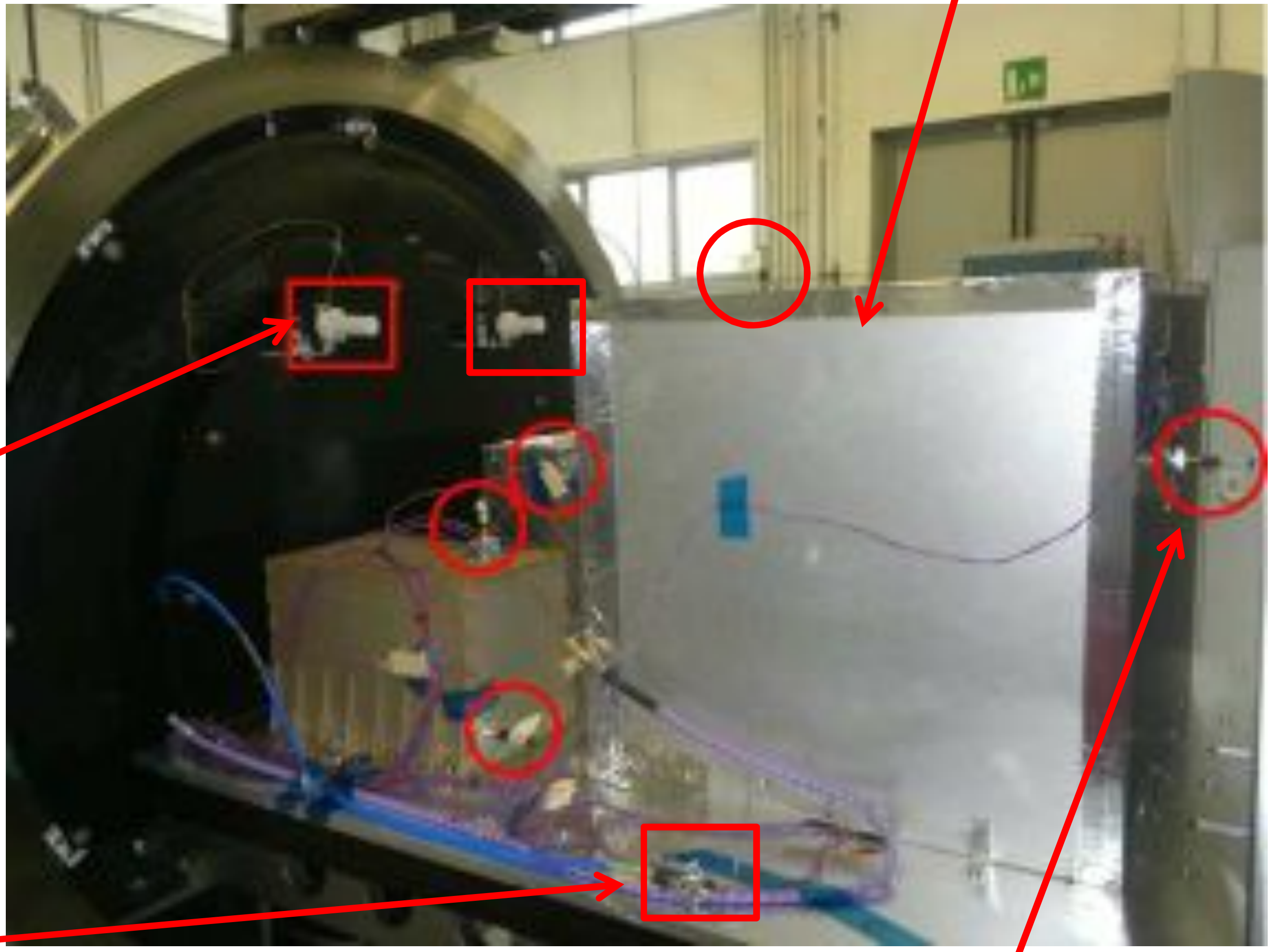
➢ Test bed implementation - primary cavity

- SENSeOR: main wireless system with 6 sensors
- Injection antenna used to test system susceptibility against interference RF noise (as verification of EMC tests in anechoic chamber)

View of open chamber

Palamede case (secondary cavity)

Interrogating Antennas



Injection antenna

(ground-plane wire antenna)

Wireless Sensor

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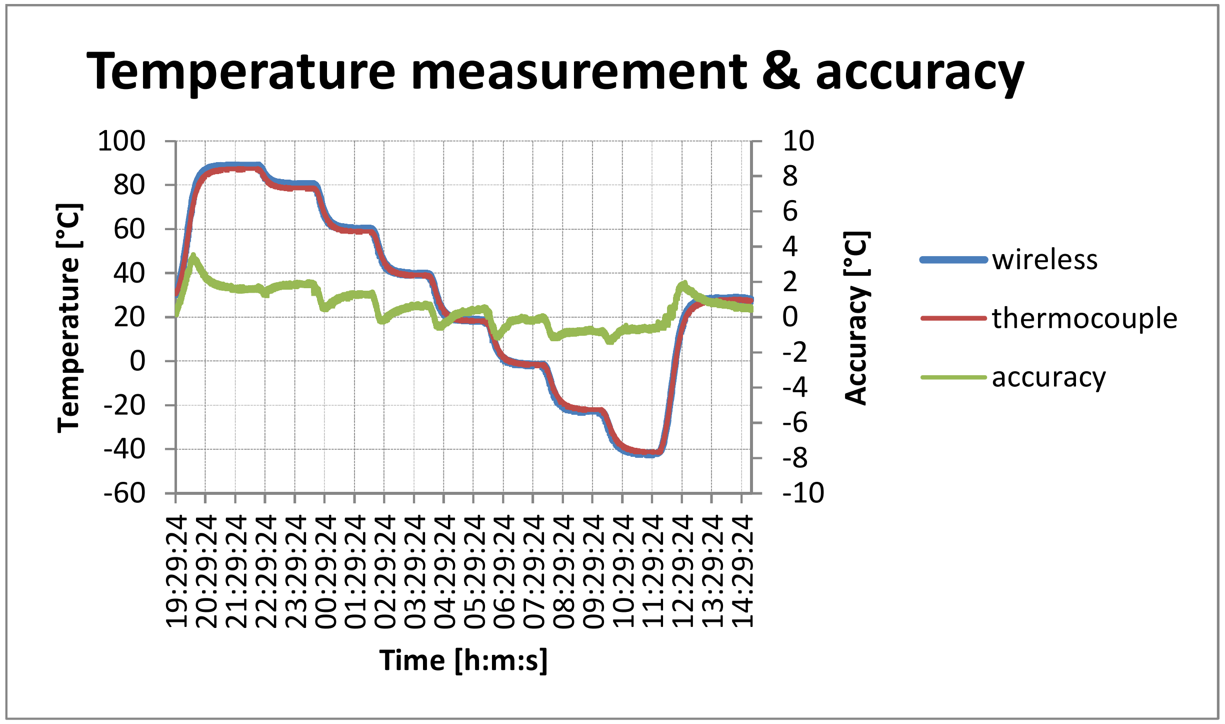
Source: SELEX ES, PoliMI, TAS, ESA ITI

➢ Temperature tests results: accuracy analysis

- Typical sensor measurement together with reference thermocouple as acquired over a temperature cycle
- Sensor and thermocouple overlap with the accuracy indicated by the green curve, accuracy being the difference between sensor and thermocouple temperatures
- It is clearly noted the effect of the thermal time constant of the commercial sensor package, observed as a delay versus thermocouple reading during thermal transitions
- The sensor outline has to be newly designed for the intended application
- Accuracy of ±2° C is generally achieved



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Source: SELEX ES, PoliMI, TAS, ESA ITI

Wireless Power Transmission and Fractionated Spacecraft

Potential applications in Space?

- Fractioned spacecraft applications
- Vehicles/robot power recharge
- Multiband - power+comm
- Attitude detection
- Formation control (induction)

Why Near-Field devices?

- Improvement in efficiency

Concept for System F6 ,Orbital Science Corporation

Fractionated Spacecraft

First engineering proposal for a fractionated spacecraft in 1984

– [Molette, Cougnet et al., 1984]

Parameters

– Modular design allowing separation of key functions of a traditionally monolithic spacecraft, e.g. power system, communication system, instruments/payloads
– Several degrees of fractionation possible

Drivers

– Simplification: the complexity and the cost of an engineering system scale exponentially with respect to a system's capability, since the assured delivery of capabilities necessitates making the system robust to various uncertainties, failure modes, and the mechanisms to addressing these, which themselves grow with the system's complexity. ("cost-complexity death spiral")
– Adaptability: quickly launched and added modules promise to adapt the capabilities of the entire system to new needs in a flexible manner
– Robustness: Redundancy in the main functions allows loosing parts of the system while still keeping it at operational level until damaged elements are replaced
– Launcher options: due to the limited mass of individual elements, in principle more launchers could be used;

O. Brown and P. Eremenko, "The value proposition for fractionated space architectures", in *Proceedings AIAA 2006*, 2006.

WPT and fractionated spacecraft

WPT as a *enabling* technology for fractionated spacecraft

- Power subsystems represent substantial parts of the overall system mass of spacecraft and impose conditions to the design and operation of a spacecraft.

Jamnejad and Silva, 2008

- Analysis of WPT options for fractionated spacecraft, assuming a resource spacecraft and smaller payload spacecraft
- Antenna size constraints
  - emitting antenna diameter: <50m
  - receiving antenna diameter: 1m
- Analysis of combinations of frequencies and distances
- System mass trade-off for frequency choice:
  - the higher the smaller the antennas
  - the higher the lower the microwave generation and conversion efficiencies
- Recommendation to put special development efforts on: efficient rectenna diodes, phased array antennas, high breakdown/low loss transmit filters, phase shifters, and retro-directive systems

WPT for fractionated spacecraft

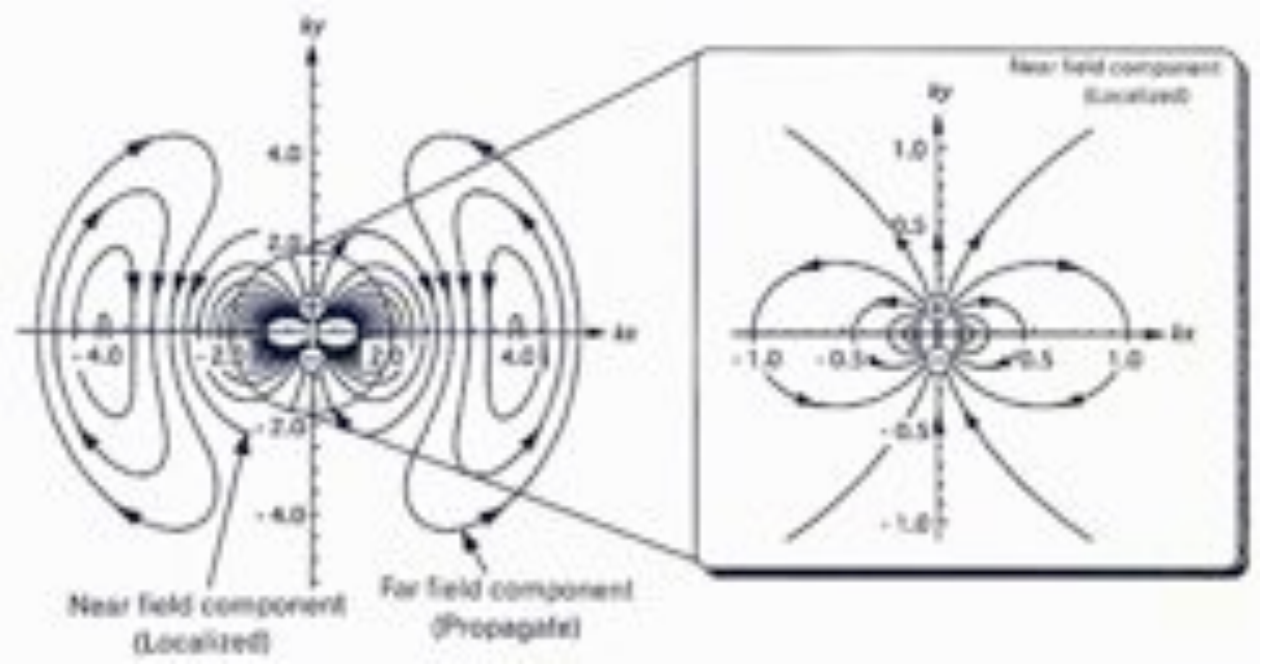
Turner et al, 2006

- Proposed a new innovative concept for transferring power within a fractionated system,
- Based a resource spacecraft that distributes high-intensity beams of unconverted concentrated sunlight to high-temperature compact receivers on receiving spacecraft, which use heat engines to generate power from heat stored in receiver reservoirs
- System thus providing routine and contingency energy storage
- Estimated power transfer efficiency around 25%

Lafleur and Saleh, 2009

- Analysed space to space wireless power transmission options, especially for small spacecraft
- concluded that the design space for power beaming is severely constrained, requiring high transmission frequencies and large antenna diameters, and stringent proximity distance.
- 1m diameter for both transmitting and receiving antennas
- 33 GHz frequency
- distances in the order of 100 m
- Unfavourable preliminary conclusions for WPT for power beaming between small spacecraft
- each small spacecraft would be required to generate 90% of its need from an on-board power source, only 10% from WPT

Near Field Wireless Power Transmission



Near field WPT usually quickly discarded from options

Principle:

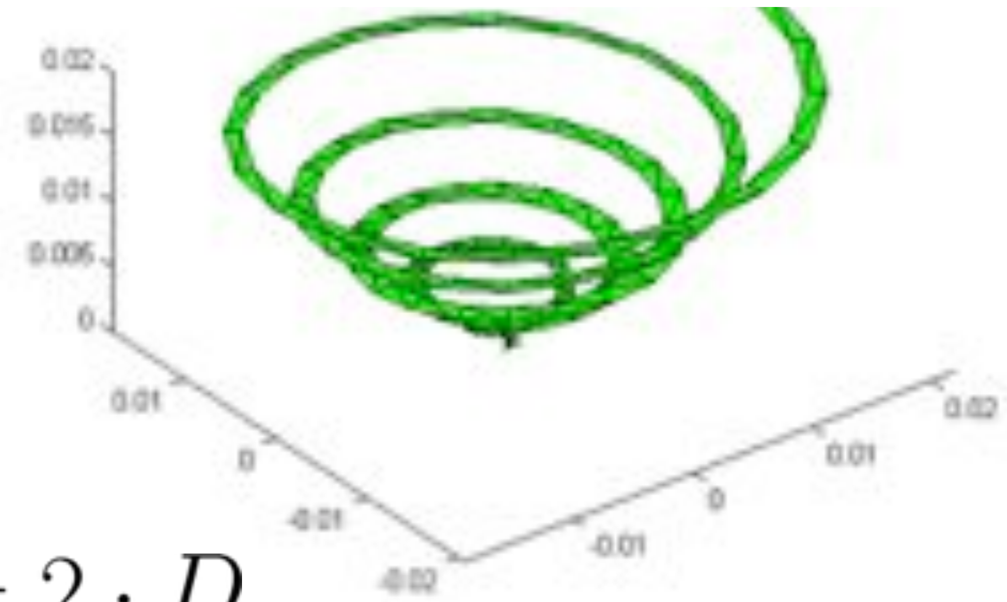
- Near field: inside λ (one wavelength) distance, strong inductive and capacitative effects; with distance, effects decrease fast in power,
- static case: these fields are simply the electro-static fields
- non-static case: formation of time varying electric and magnetic fields, which are out of phase close to the object (closer than λ), and can be used to induce current in near-by objects
- advantage in efficiency as near fields do not radiate energy away from the source
- Magnetic induction between two close-by antennas; increased effect under resonance

magnetically coupled coil resonators

Near Field "Antenna" Optimisation

1.Geometry

Parameters
Number of Triangles
Length
Number of Turns
Thickness
Z-axis (6p.)
Diameter (6p.)

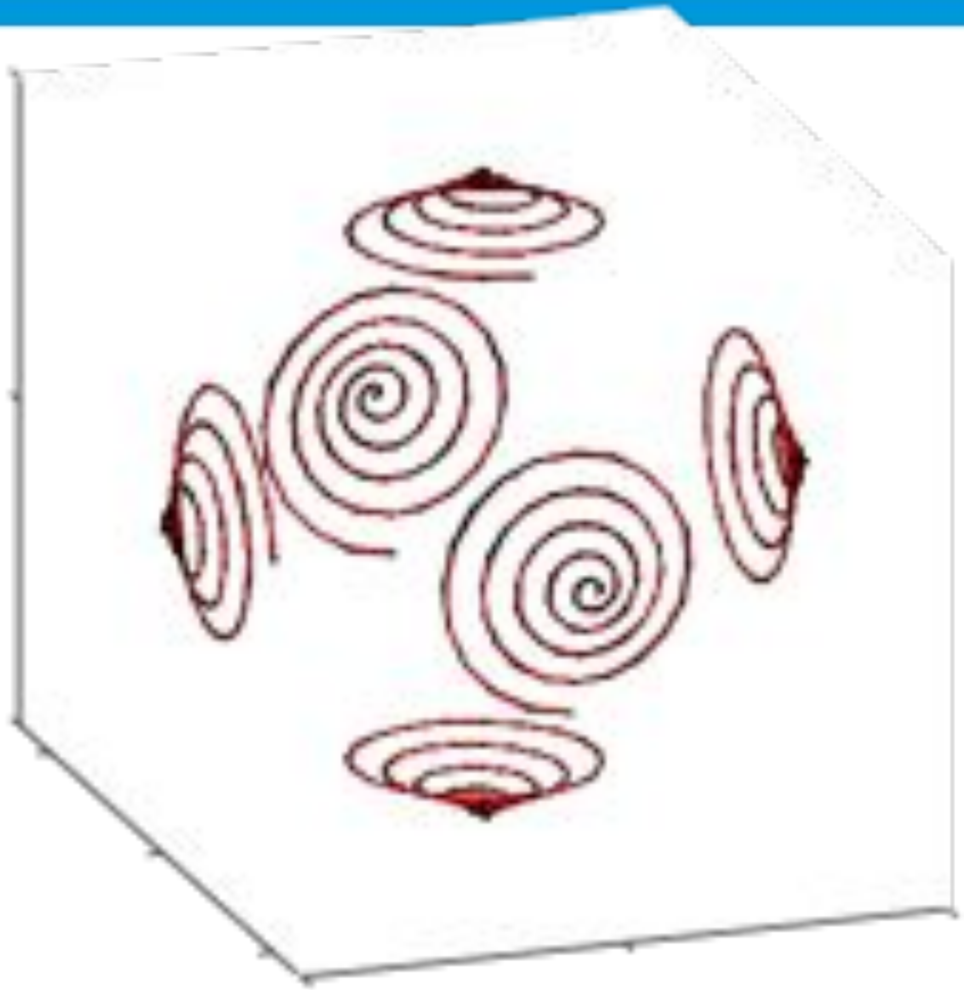


Non-geometrical: frequency

$$W = 2 \cdot D$$

Versloot et al, EUCAP 2014

Near Field "Antenna" Optimisation



MoM in multi-"antenna" scenario

- Complexity in Impedance Matrix

$$[Z] = \begin{bmatrix} [Z]_{ant1,ant1} & [Z]_{ant1,ant2} & \cdots & [Z]_{ant1,antN} \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ [Z]_{antN,ant1} & \cdots & \cdots & [Z]_{antN,antN} \end{bmatrix}$$

Versloot et al, EUCAP 2014

Near Field "Antenna" Optimisation

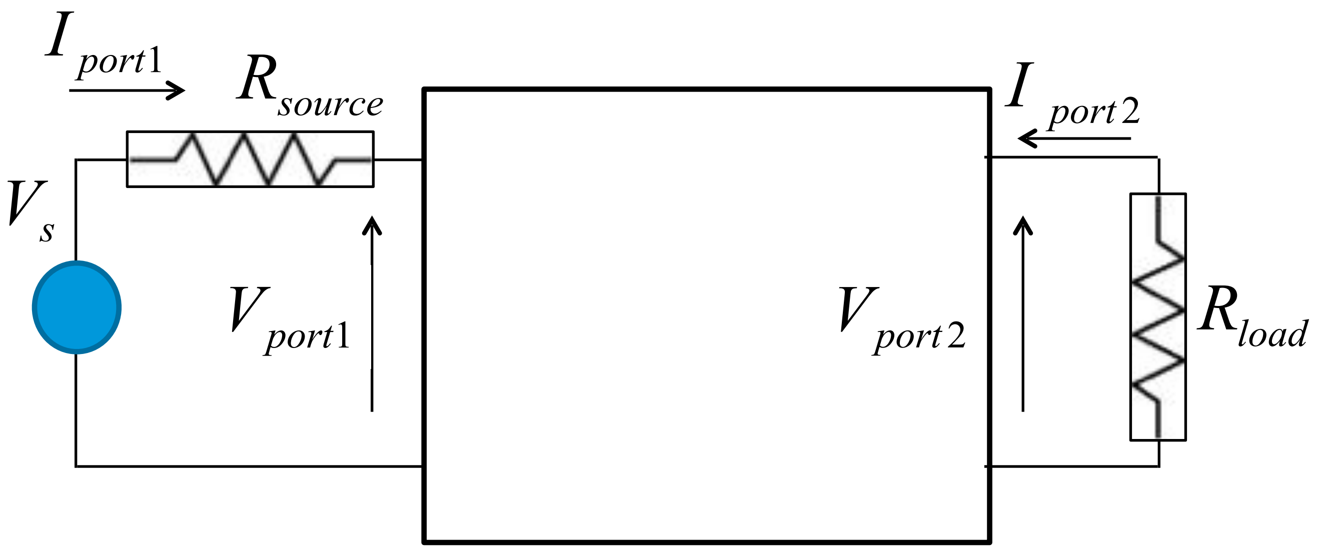
2. MoM in Multi-"antenna" scenario

Moment Equation (simultaneous solving applying loads)

$$[Z] \cdot [I] = [V]$$

$$V_S = V_{port1} + R_{source} \cdot I_{port1}$$

$$V_{port2} = -R_{load} \cdot I_{port2}$$



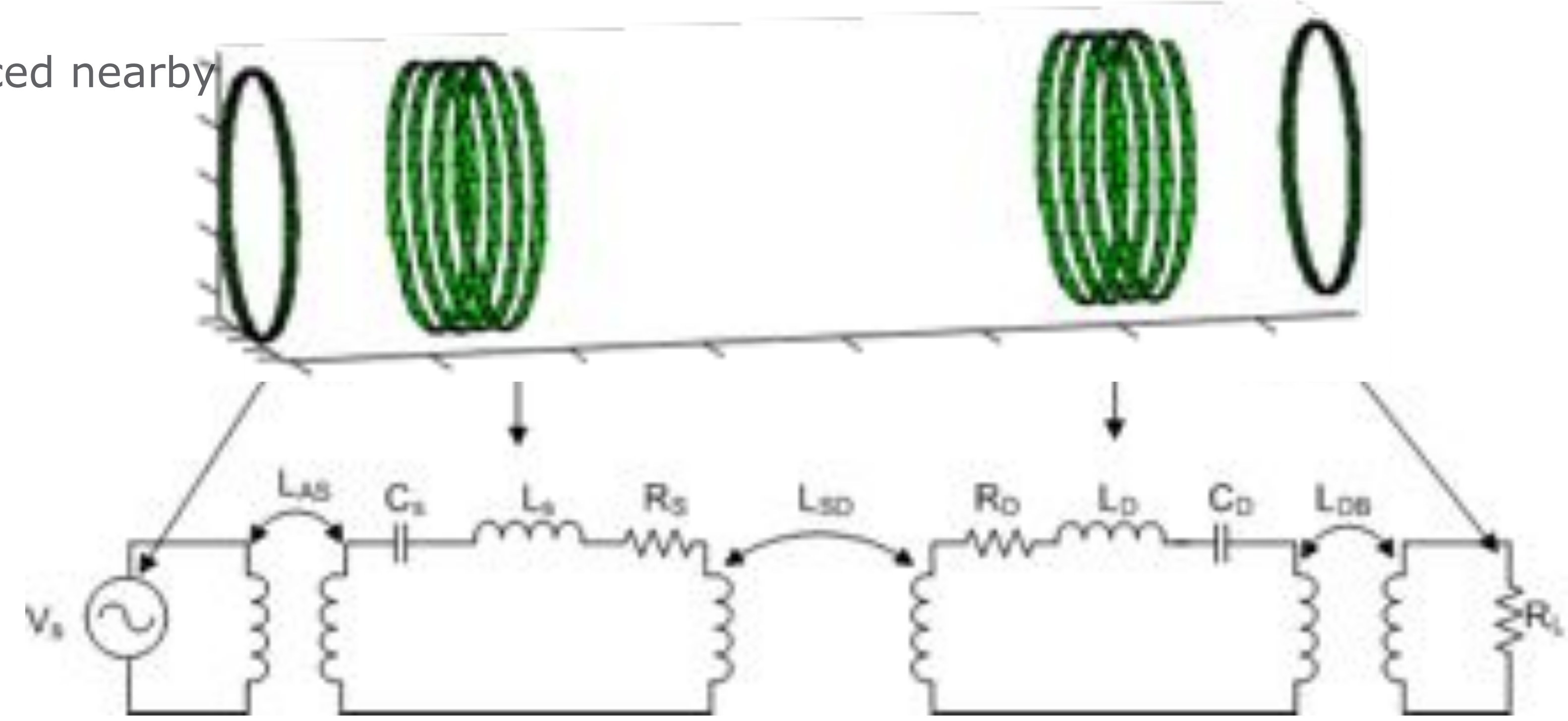
Versloot et al, EUCAP 2014

European Space Agency

Near Field "Antenna" Optimisation

3. Near Field Computation

- NF are electric and magnetic fields produced nearby



Lumped Element

Example 4 antennas

- Two drive loops
- Two coil resonators

Power transfer ratio:

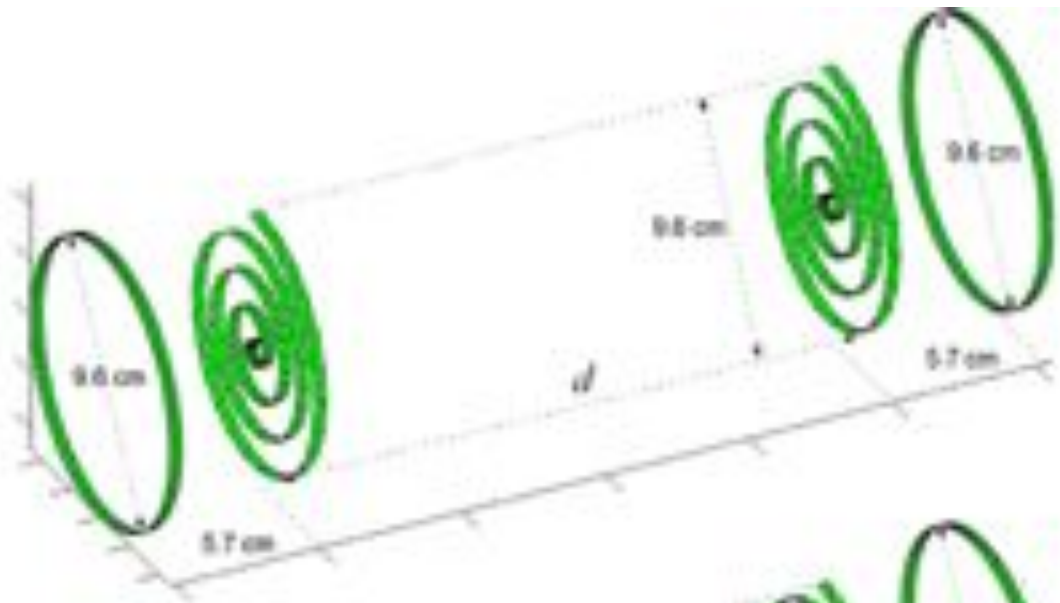
$$\frac{P_{out}}{P_{input}} = \frac{Real\{V_{port2} \cdot I^{c}_{port2}\}}{Real\{V_{port1} \cdot I^{c}_{port1}\}}$$

Versloot et al, EUCAP 2014

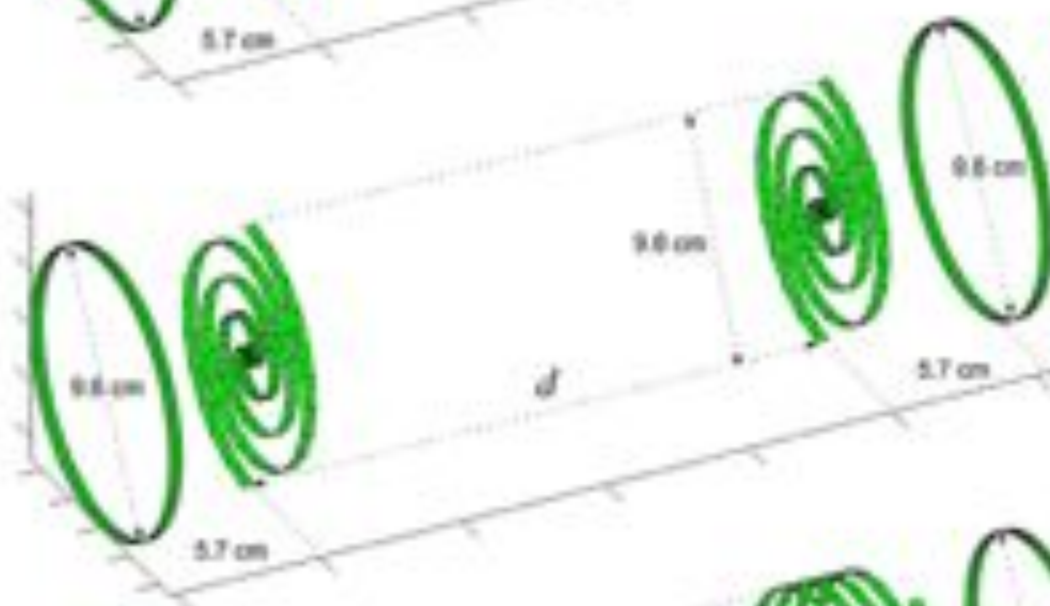
Near Field “Antenna” Optimisation

Standard geometries - Multiple Coils

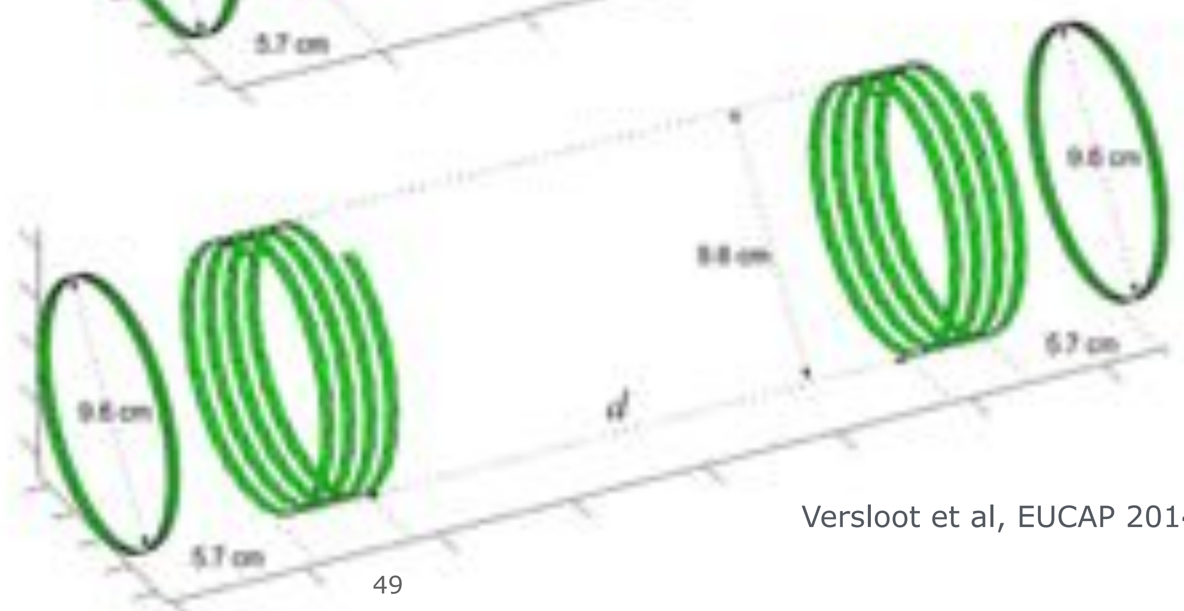
Archimedean Spiral



Fermat´s spiral (2 branches)



Solenoid



Versloot et al, EUCAP 2014

Near Field "Antenna" Optimisation

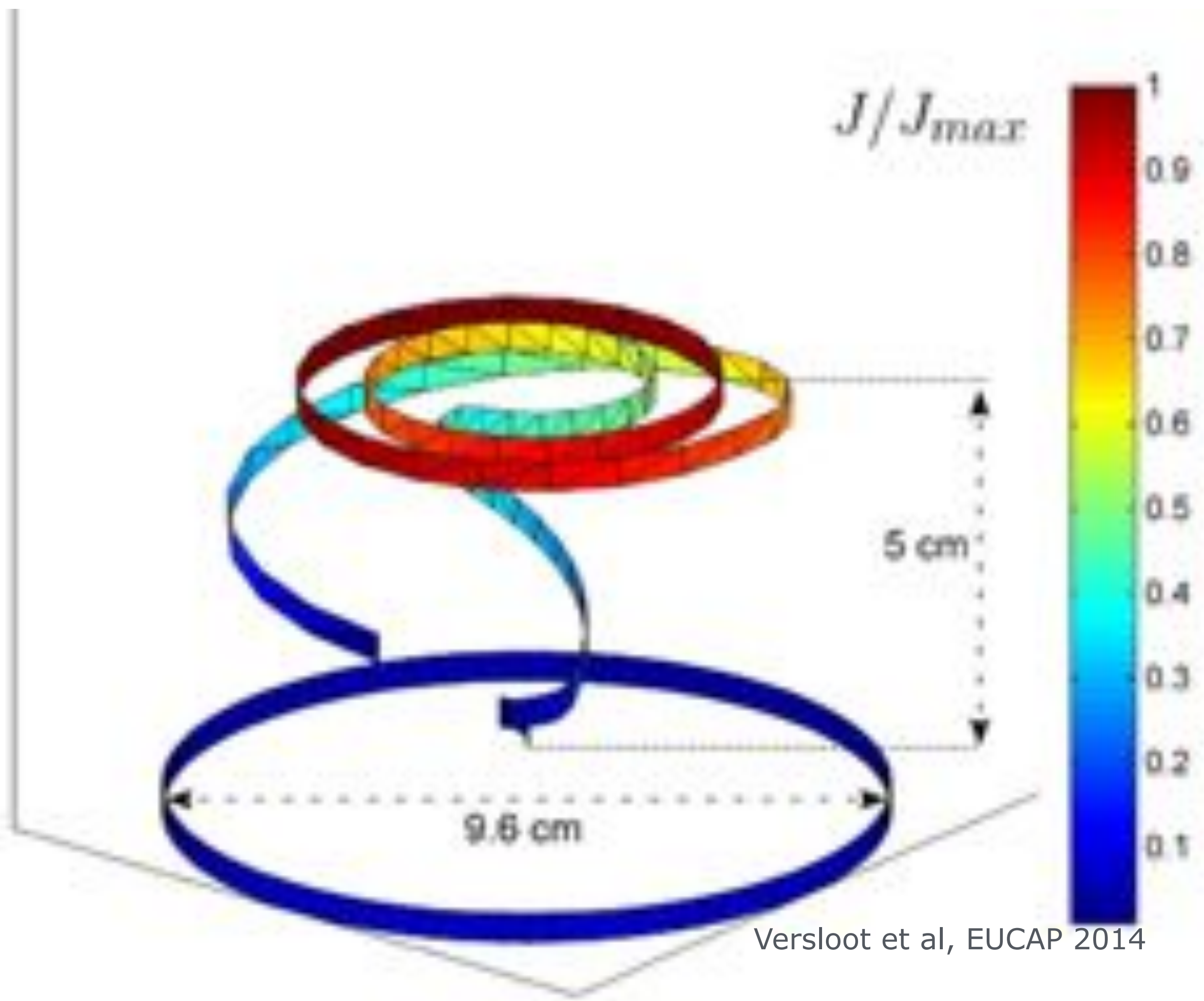
Optimisation of Maximum Pout/Pin between 2 coils

Optimisation Parameters

Evolved Antenna Shape

Parameter	LB	UB
Turns	1	6
Z-axis (6)	0	λ/2
Frequency (%)	-25	+25

Important to add frequency!



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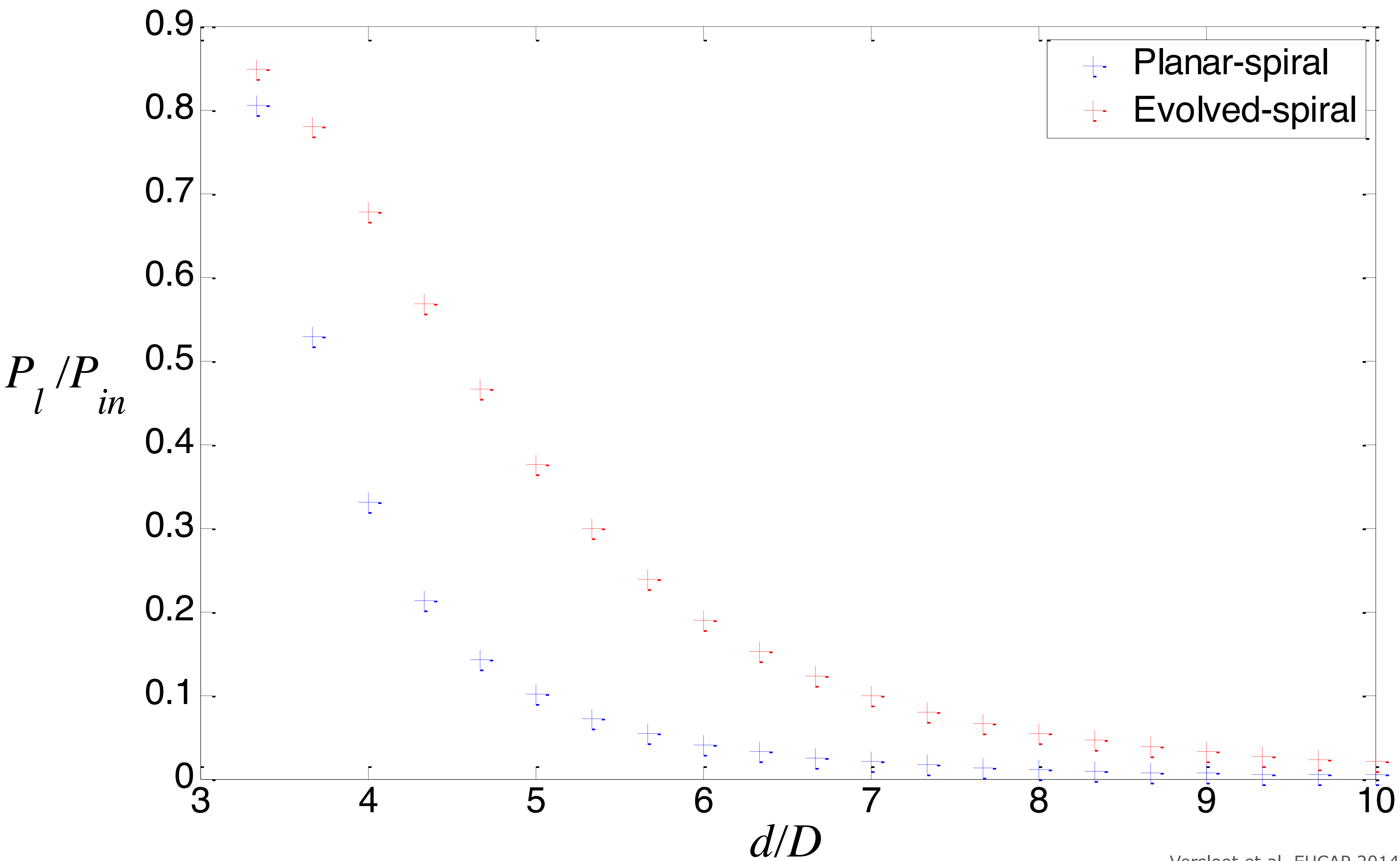
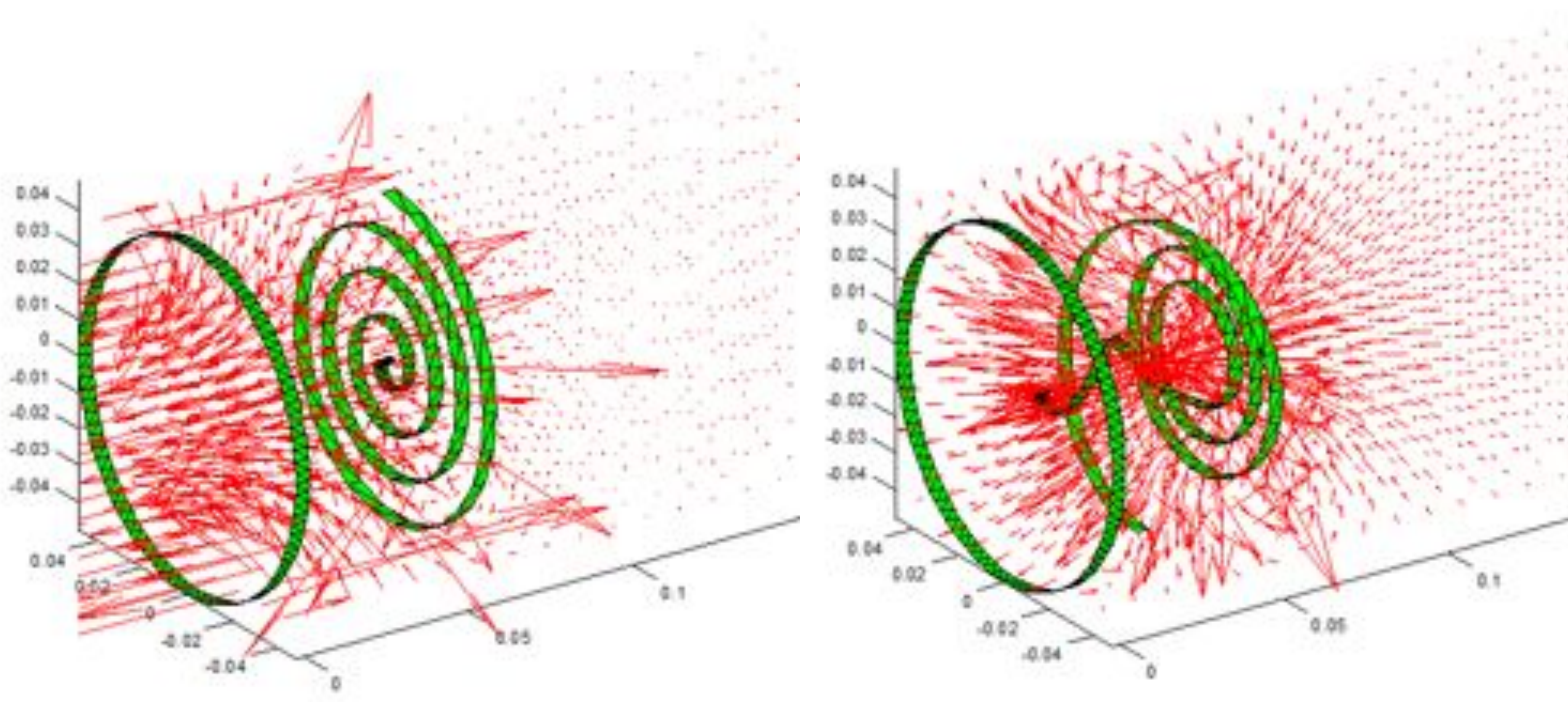
Near Field "Antenna" Optimisation



Versloot et al, EUCAP 2014

Near Field "Antenna" Optimisation



Versloot et al, EUCAP 2014

Near Field "Antenna" Optimisation

$$\frac{d}{D} = 4$$

GEOMETRY	EVOLVED	SPIRAL	SPIRAL 2	SOLENOID
Transfer (%)	0.68	0.35	0.17	0.2
Frequency (MHz)	200.8	212.1	422.1	88

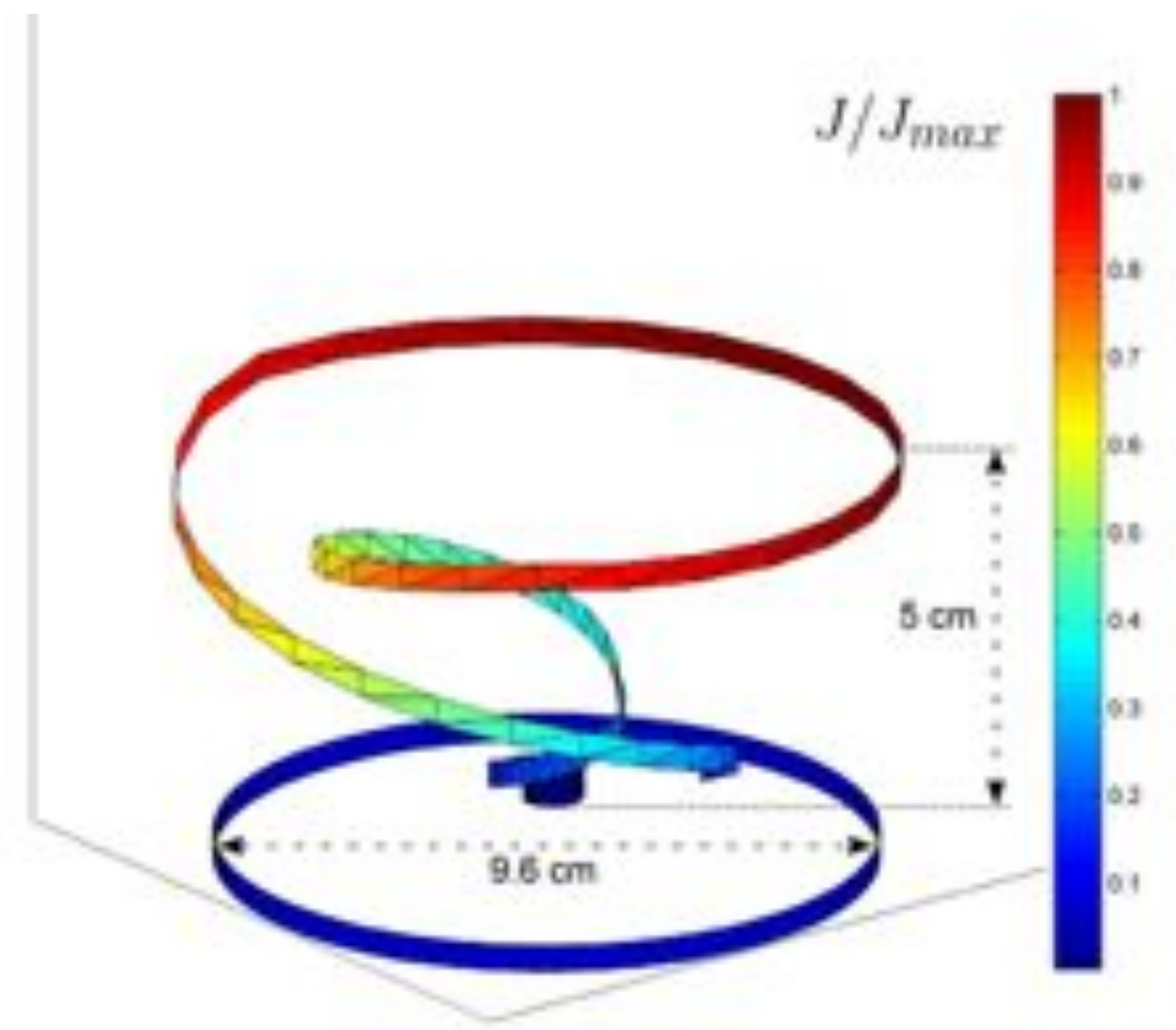
Versloot et al, EUCAP 2014

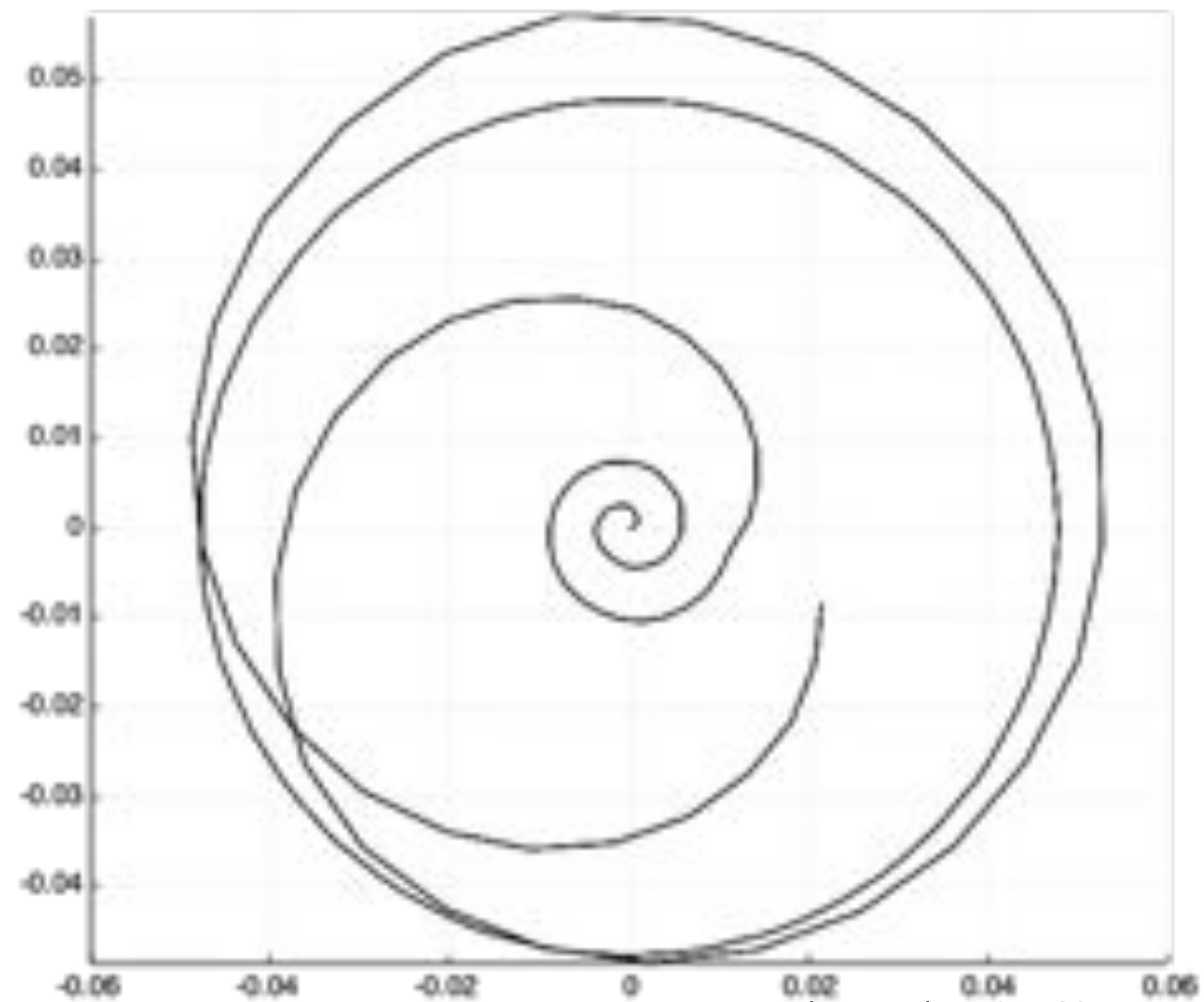
Near Field "Antenna" Optimisation

Evolved Optimisation of bandwidth

Goals:

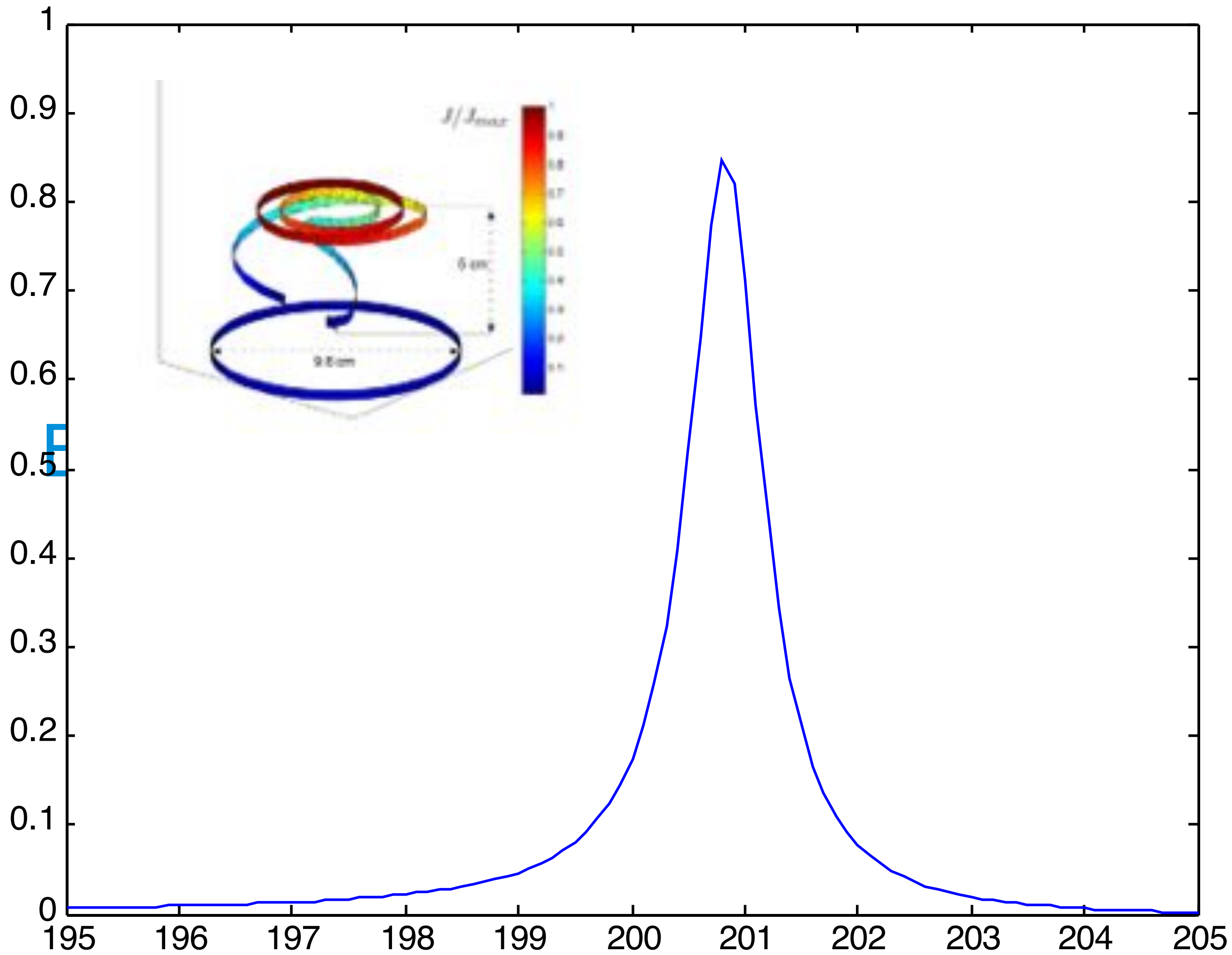
- Increase the frequency robustness
- Other applications (multi systems)

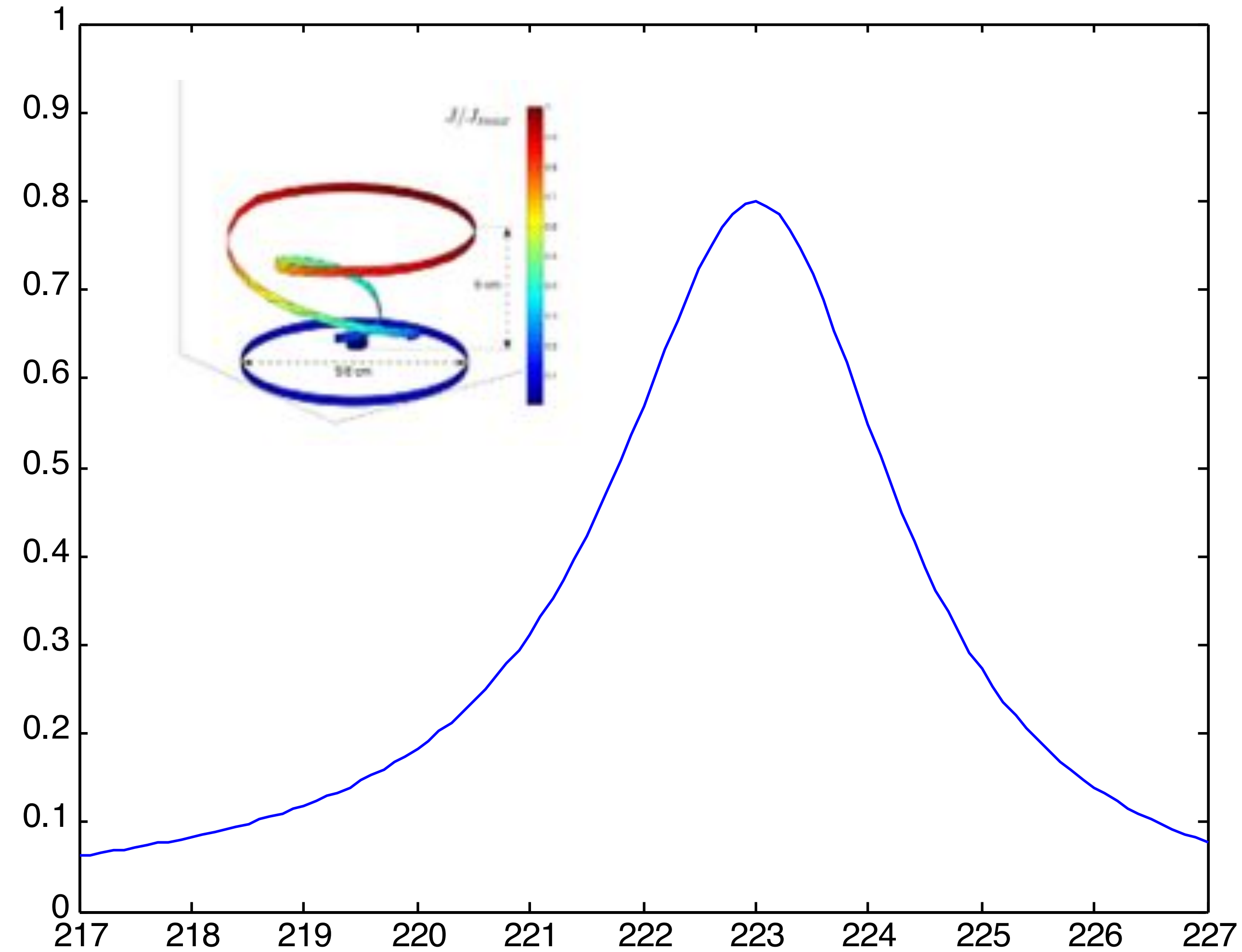




Versloot et al, EUCAP 2014

Near Field "Antenna" Optimisation





Versloot et al, EUCAP 2014

Near Field "Antenna" Optimisation

Conclusions

- evolved a single coil shape to maximise its magnetic flux.
- improved Pout/Pin of the spiral resonator from 0.35 to 0.68 by evolving it with a GA.
- improved the bandwidth so that both communication and power signals can be transmitted using the same system.
- Adding complexity into the geometry can improve the results (better discretisation, much more freedom). Limited by: computation time
- Adding complexity into the fitness function can improve the results (e.g. 5 frequency search problem). Limited by: computation time!

Versloot et al, EUCAP 2014

Near Field "Antenna" Optimisation

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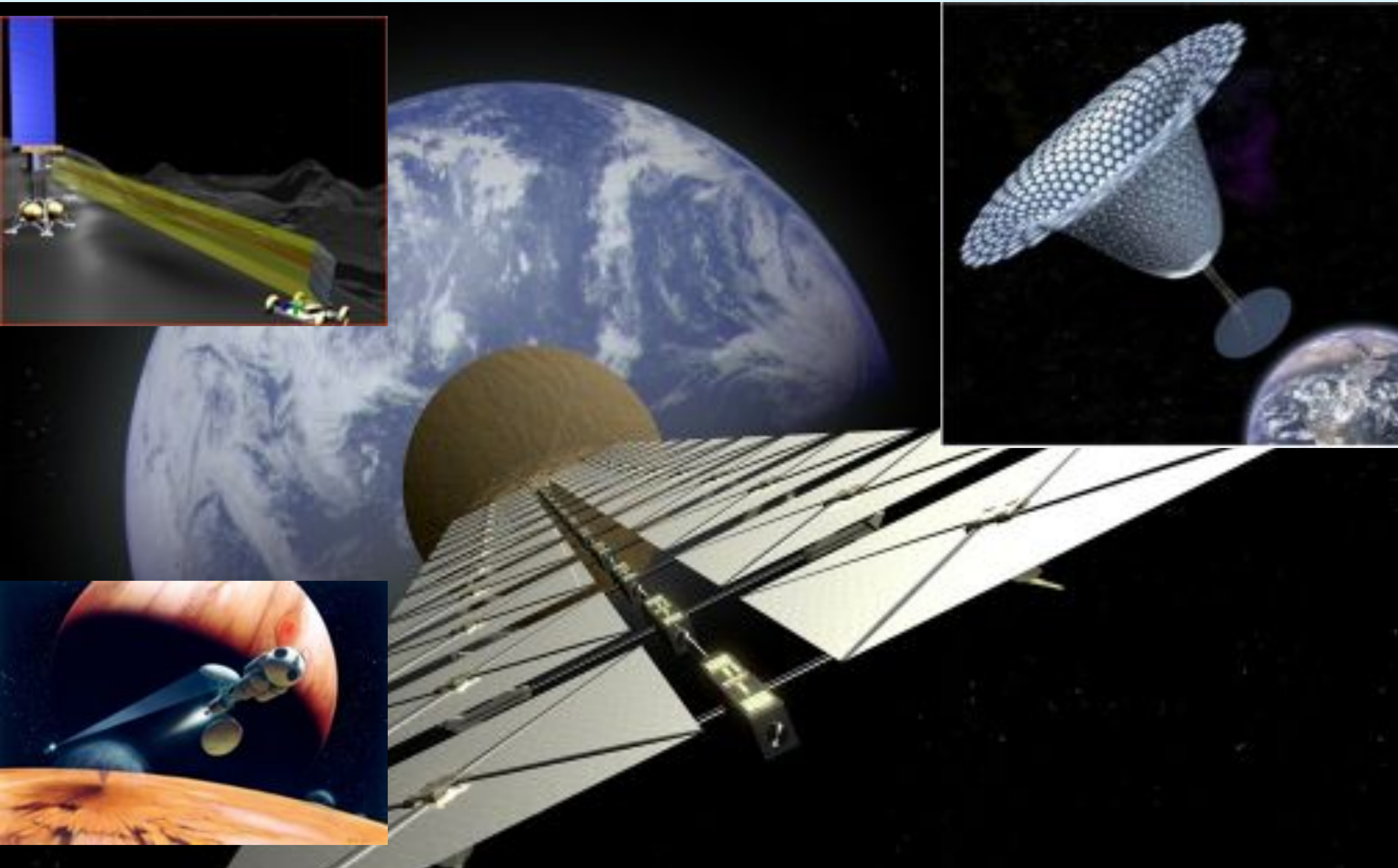
Versloot et al, EUCAP 2014

Large distance power transmission



Large distance power transmission
Context

Supporting the Energy Transitions

- Solar power will play an important role in the world's future energy supply.
- Terrestrial solar plants are rapidly expanding (6.4% growth p/yr) and costs (€/W) are dropping
  -> Could concept of solar power from space to earth benefit from these developments.
- Space and time localisation of solar sources emphases the need for large-scale grid storage
  -> SPS could alleviate need for expensive local storage

ACT-ESA activities:

- maturing technologies via research and experiments
- latest work focused on market opportunities and integration of space and terrestrial activities.
- investigation of other applications and potential later dual use of SPS architecture (e.g. hurricane control)

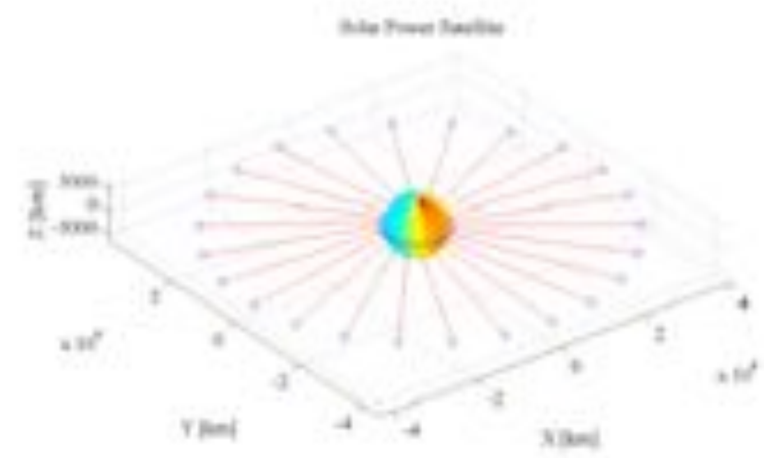
Large distance power transmission
SPS to complement terrestrial energy supply

Motivation: use global optimisation tools to investigate the combination of terrestrial and space power stations (Europe only)

Currently, high cost of storage/linkage

- Fuel cell (50% efficiency) in combination with storage tanks (73% efficiency)
- Loss in transmission lines (3%/1000km)
- Relatively high capital costs

Optimise number of base stations required to minimise total costs, storage capacity and cabling infrastructure



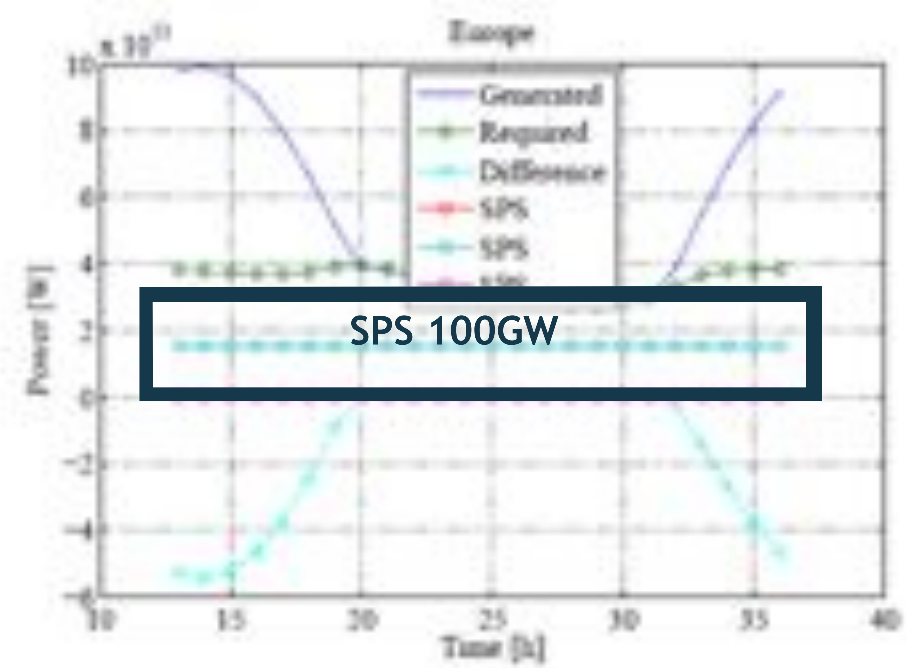


Figure 12. Example of mix between SPS and ground station for a three stations scenario

-> Multi-station (3) optimal
-> SPS: Decrease peak power generated during day by 30%
-> Integration promising to reduce the need for storage

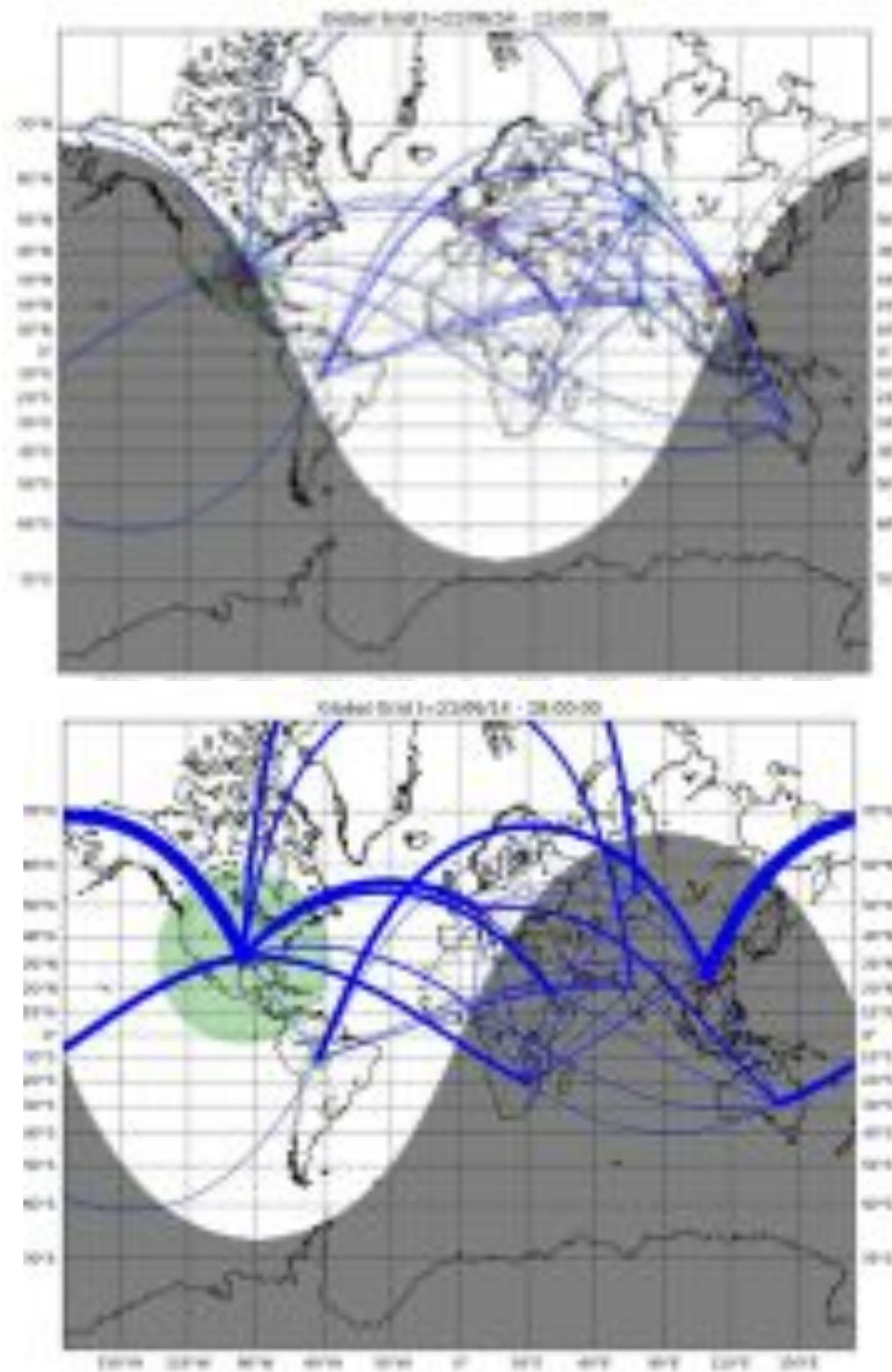
M. Vasile & L. Summerer, IAC Conference Prague 2010, C3.1.5

Large distance power transmission
Next step: global interconnected grid

Motivation:

- Investigate mismatch in terrestrial solar supply and demand with global hourly model
- Multi-objective optimisation strategy to explore minimal SPS power levels that can compete with storage or long-distance transmission lines
- Minimise storage capability and solar area required
- Combine rectenna arrays and solar farms to share terrestrial distribution networks

-> day-night cycle and cloud coverage taken into account
-> terrestrial plants advantageous over space plants until several tens of GW



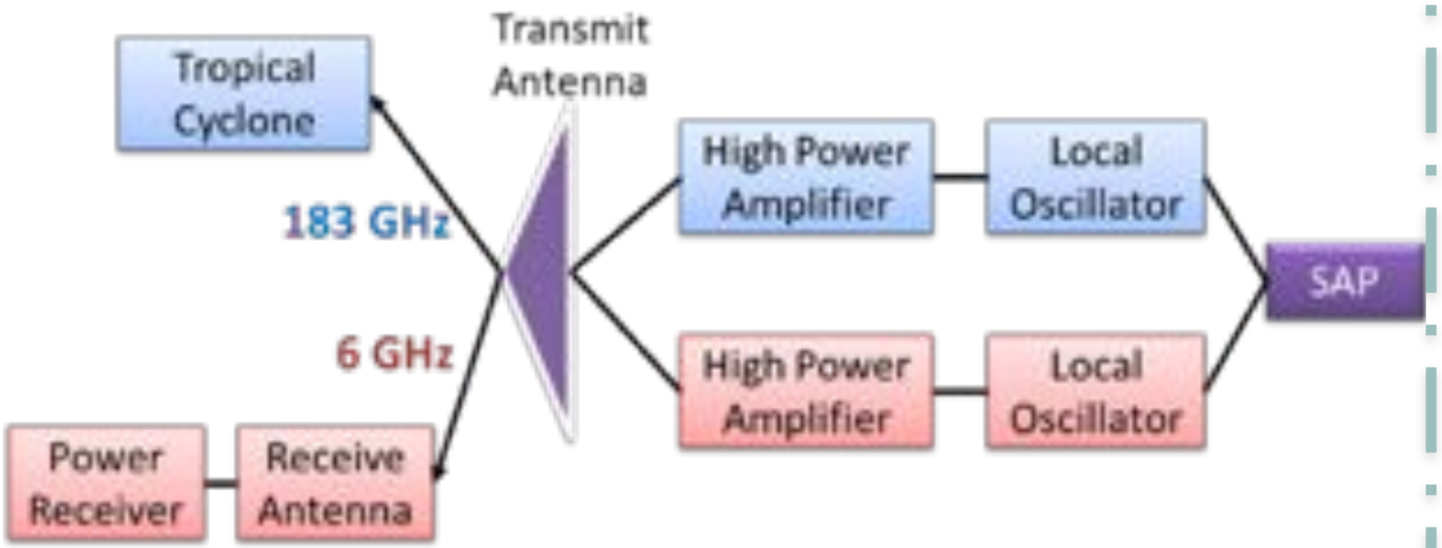
Preliminary results - on-going work - T. Versloot et al.

Large distance power transmission
Most Devastating Cyclones

Name	Date	Place	Death toll	Wind speeds	Damage
Hurricane Katrina	2005	**USA**	1833	280 km/h	$108 billion (2005) USD
Typhoon Nancy Muroto)	1961	**Japan**	191	345 km/h	$500 million (1961) USD
Typhoon Bess	1982	**Japan**	95	260 km/h	$2 billion (1982) USD
Hurricane Andrew	1992	**USA**	26	280 km/h	$27 billion (1992) USD

Large distance power transmission
Impeding the development of TC

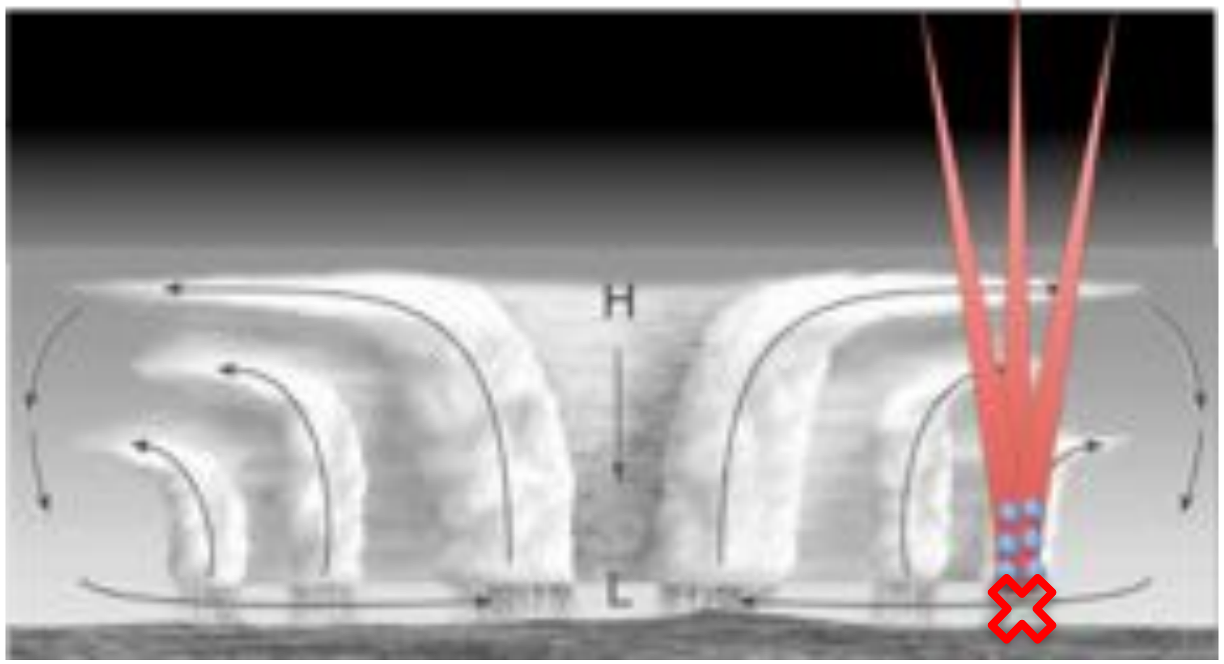
Microwave-based atmospheric heating [μ-SPS]



-> 183GHz: heat the atmosphere via H_2O resonance

-> TC intensity α $\Delta T = T_{sst} - T_{atm}$

Laser-based cloud seeding [L-SPS]



-> Grow outer clouds by adding rain seeds using femtosecond filamentation

I. Dicaire, R. Nakamura, Y. Arikawa et al, submitted

Large distance power transmission
Physical Model of Laser Filamentation

High Intensity -> Optical Kerr Effect -> Focusing lens

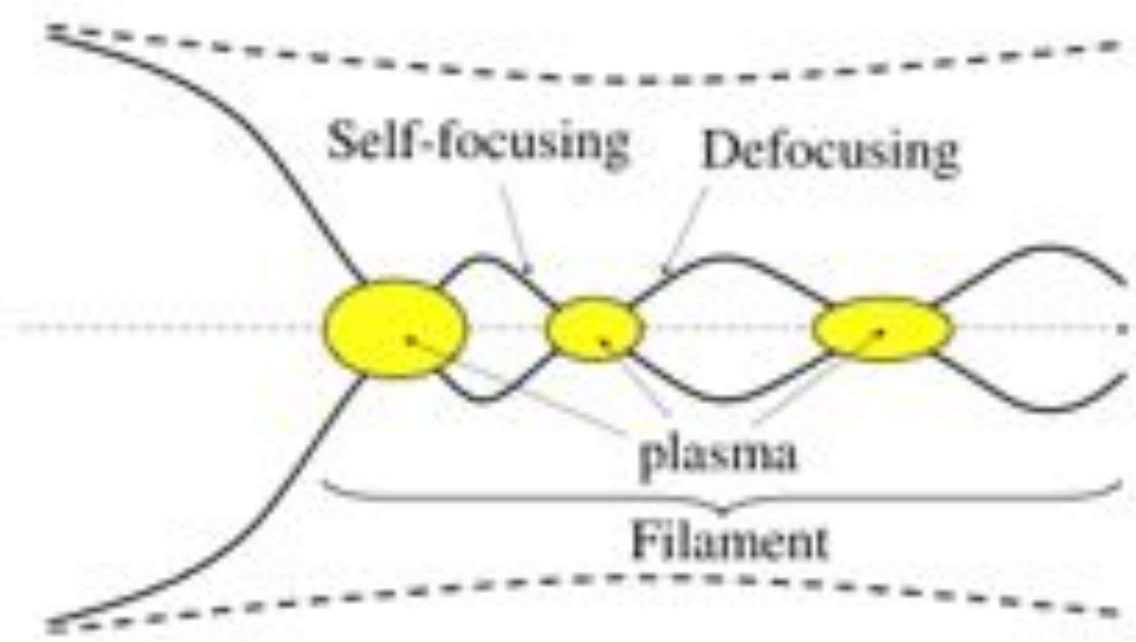
$$n(r,z) = n_0 + n_2 I(r,z) = n_0 + n_2 I_0 \left(\frac{\omega_0}{\omega(z)}\right)^2 \exp\left(-\frac{2r^2}{\omega(z)^2}\right)$$

High Intensity -> Plasma Generation -> Defocusing lens

Self-guiding: no beam divergence

$$n^2 = 1 - \frac{Nq^2}{m\varepsilon_0\omega^2}$$

(Multiphoton Ionization, Free Electrons)



- Solid curve -> 100µm size filaments intense core 10^{13} W/cm^2
-- Dashed curve -> laser energy reservoir

From A. Couairon and A. Mysyrowicz. *Physics reports* 441.2 (2007)

Plasma: generate rain seeds [HNO_3] via effective photochemistry

Large distance power transmission
Cloud Seeding via Laser Pulses

① An excess of rain seeds will reduce precipitation, the rain drops will stay in the cloud and ascend above the 0°C isotherm.

② Thunderclouds grow. The original eye wall weakens as the **second eye wall grows.**

③ Eye wall reforms at larger radius, **decreasing wind velocities** due to conservation of angular momentum (**L**=**r** × m**v**).

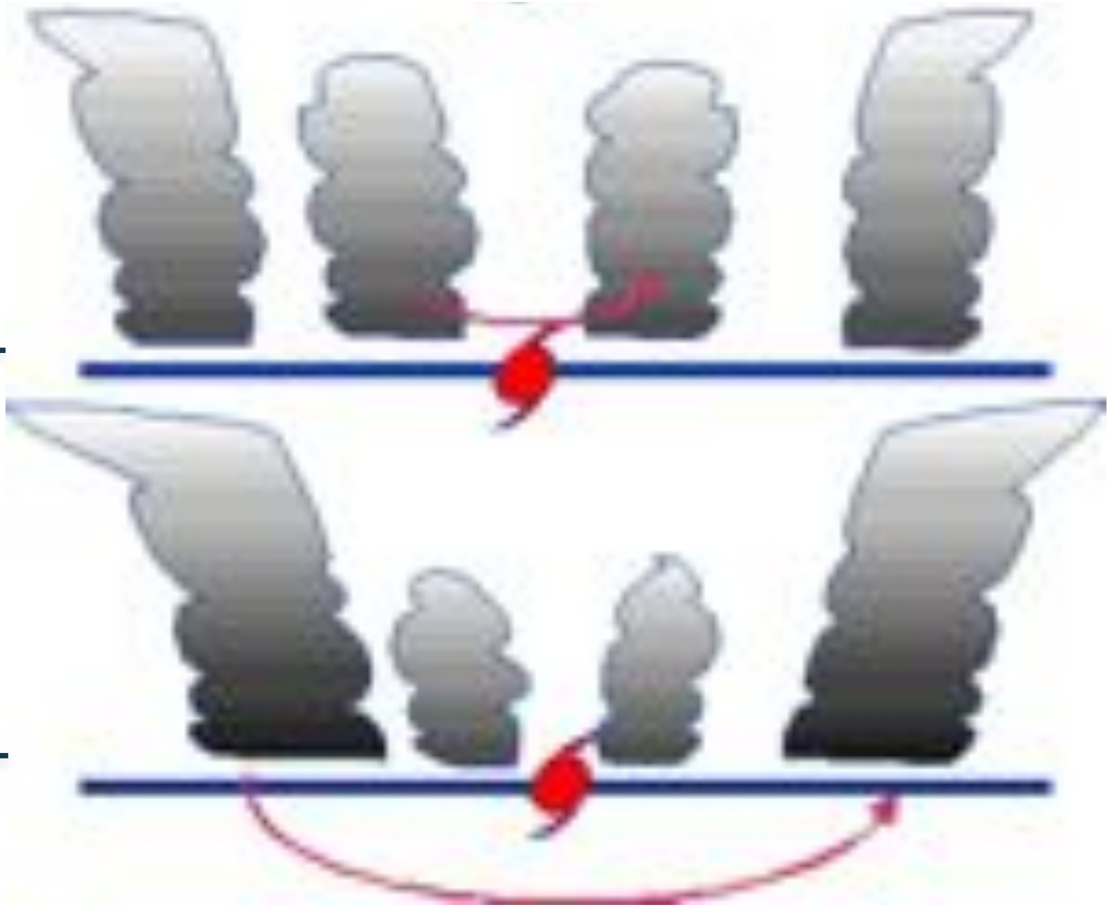


Image credit: U.S. NOAA

Large distance power transmission
System Specifications

Microwave-based atmospheric heating [μ-SPS]

μ-SPS Space System Specifications	
SPS capacity	1.5GW
Irradiation area	100x100km
Irradiation frequency	183 GHz
Irradiation time	2 days

Laser-based cloud seeding [L-SPS]

Laser Filamentation Characteristics	
Pulse wavelength	λ=800-1000nm
Pulse duration	< 240 fs
Pulse energy	> 160 mJ

⇨ 10^5 CCN* cm^{-3}

Ground Demo Specifications	
Dimensions	6m×2m×2m
Weight	10 tons
Power consumption	30 kW

-> Future work: perform a space system in-depth study and analysis

Large distance power transmission Technology Roadmaps

Microwave-based atmospheric heating

	2011-2020	2021-2030	2031-2040
Earth Meteorological System			
Numerical weather model	10m, 200km	1m, 20km	10cm, 2km
Super computer	10^{15} FLOPS	10^{18} FLOPS	10^{21} FLOPS
Total system assimilation	R&D		Ground demo
Heat Irradiation System			
Space Solar Power Satellite (SSPS)	Space demo, 100 kW	Space demo, 2 MW	Space demo, 1GW
Energy transmission	R&D	Ground demo	Space demo
Beam pointing	R&D	Ground demo	
Frequency switching	R&D	Ground demo	

Laser-based cloud seeding [L-SPS]

	2011-2020	2021-2030	2031-2040
Laser-induced Cloud Seeding System			
Laser Solar Power Satellite (L-SPS)	R&D		Space demo
Ti:Sapphire laser system	Ground demo	Space demo	
Beam Pointing	R&D	Ground demo	Space demo
Femtosecond Filamentation System	Ground demo	Space demo	

I. Dicaire, R. Nakamura, Y. Arikawa et al, submitted

Large distance power transmission
Conclusions

WPT technology could provide a space-based option to influence the intensity of extreme weather effects.

Terrestrial solar plants still have the advantage below several 10GW of generated energy.

Large distance power transmission

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Large distance power transmission

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