

The 2014 COST Summer School at Aveiro, Portugal

Microwave Power Transmission in a Spacecraft and to a Rover

Shigeo KAWASAKI

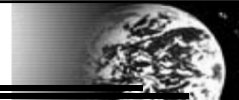
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Agenda




1. *Green-Eco Technologies*
2. *Category and Technologies of WPT and EH*
3. *Components for MPT*
4. *Compatibility of MPT with Wireless
Communication*
5. *Demonstration and Applications*
6. *Conclusion*



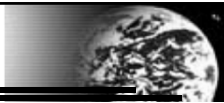
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Green-Eco Technology




Motivation

Environmental Problems


- *Energy Crisis due to shortage of fossil fuels*
- *Global Warming by CO2*

Remarkable progress on Microwave Technology

- *Wired / Wireless Communication Systems*
- *Sensors (ex. a Radar)*
- *Microwave Wireless Power Transmission (MWPT/MPT)*




Wireless Green Eco Projects



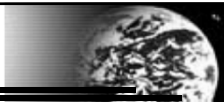
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Green-Eco Technology




Wireless Green Eco Technologies

- *Wireless Power Transmission*
(*EM Coupling / Meg. Resonance / Microwave Power Transmission*)
- *Power Recycle*
(*Power Feedback*)
- *Energy Harvesting <from Electromagnetic Wave>*
(*Solar Battery / Leaked RF and Microwave*)
- *Scavenging from Sensing and Monitoring <from Others>*
(*Action and Athletic Energy / Vibration*)
- *Green Eco Electronics*
(*Less Rear-Metal/ Rear-Earth Devices / Hybrid Semiconductor ICs*)

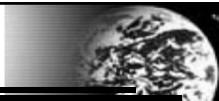


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The Category and Technologies of WPT and EH



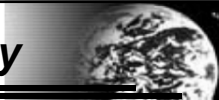
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Category and Technology



Wireless Power Transfer

||


Wireless Power Transmission
(Transmission & Propagation)

+

Energy Harvesting
(Reception & DC Power Generation)


Transmission / Propagation			
sorts	Range	Power Delivery	Functionality
EM Coupling	short	high	communication
Magnetic Resonance	medium	high / medium	power
Microwave Power Transmission	long	Medium / Low	communication, sensor & powerse

Reception / DC Power Generation			
sorts	Source	Transferred Power	Structure
Scavenging	unknown (Mechanical)	μW	simple
Harvesting	intentional & unknown (RF)	mW	medium
EM Power Receiving (Active EH)	intentional (pair with transmitting)	W	complex



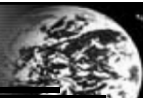
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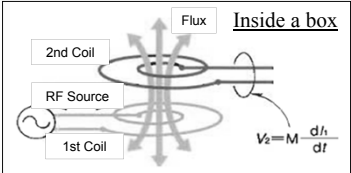


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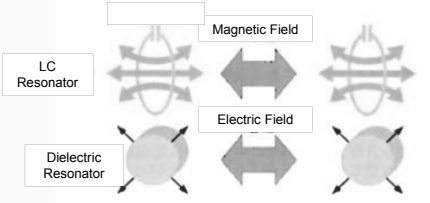
Wireless Power Transfer



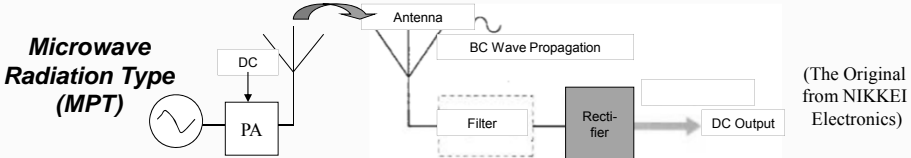
The Three Types of Wireless Power Transmission



Coupling Type




Resonant Type




Microwave Radiation Type (MPT)

(The Original from NIKKEI Electronics)



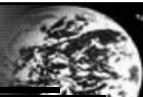
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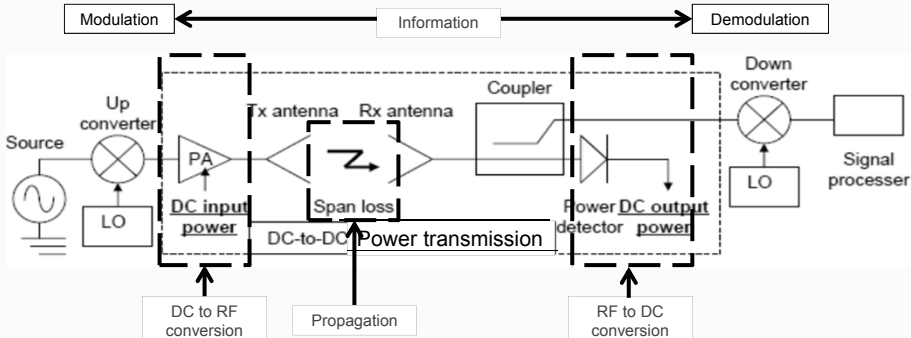


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Definition of Power Transfer



The Total Power Transmission



For MPT, DCin-to-Dcout is important



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Wireless Power Transfer Formula

The Power Delivery Rate in WPT Efficiency by Range Dependency

Magnetic Coupling and Resonance

From this, normalizing all non distance dependent variables as g

$$\eta = \frac{P_{Rx}}{P_{Tx}} = \frac{1}{1 + \frac{2}{\sqrt{1 + \frac{1}{D^6} g}} + \frac{2D^6}{g} \left(\frac{1}{\sqrt{1 + \frac{1}{D^6} g}} + 1 \right)}$$

g is an intrinsic variable from the structure of coils

Microwave Radiation

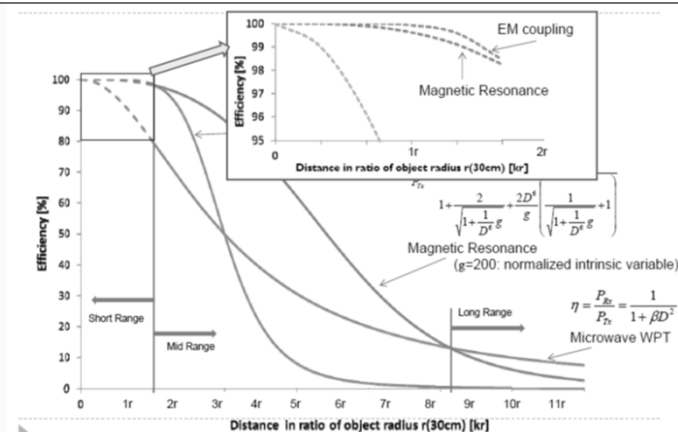
From arranging Friis' equation,

$$\eta = \frac{P_{Rx}}{P_{Tx}} = \frac{1}{1 + \beta D^2} \quad \beta = \left(\frac{\lambda}{2\pi} \right)^2 G_{Tx} G_{Rx}$$

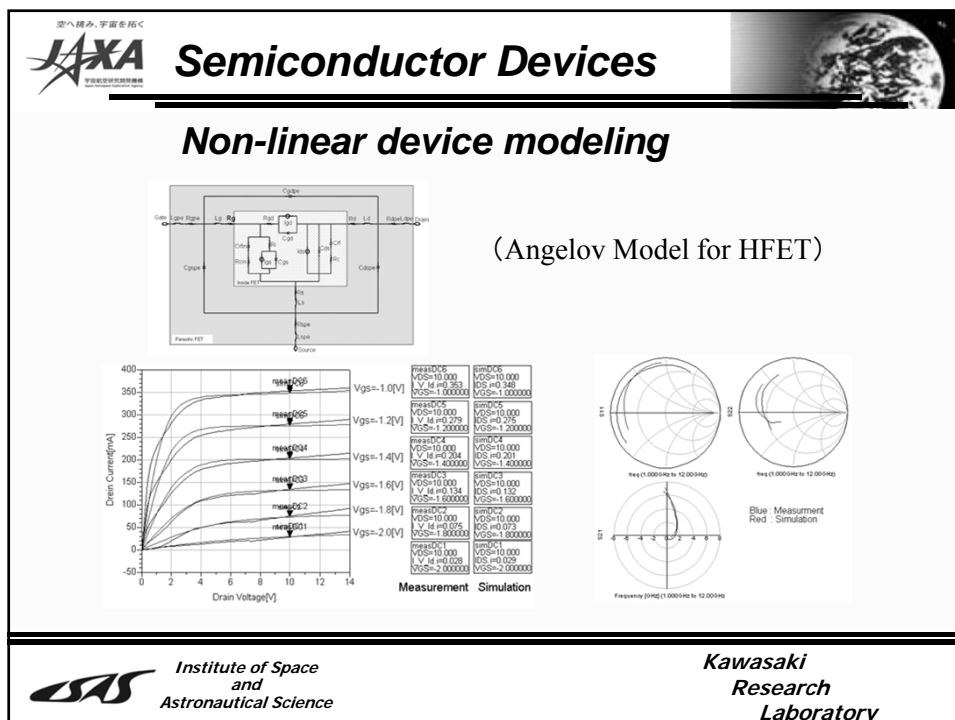
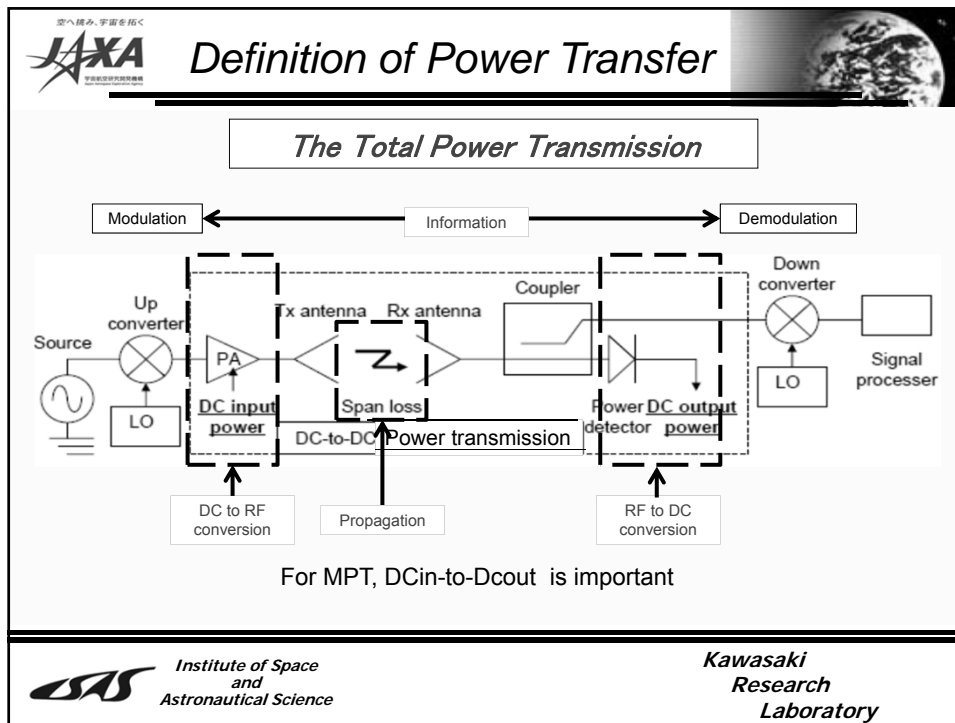
β is a variable from antenna gain and wavelength

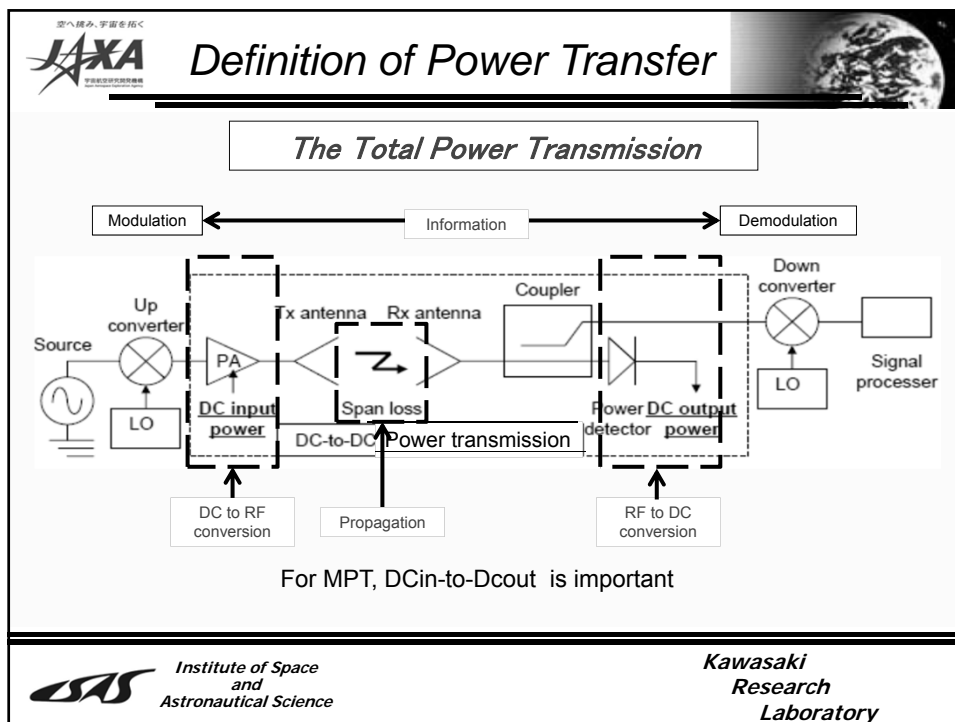
Comparison of WPT


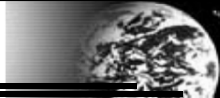
Comparison of power transmission rate of the three types of WPT



D : Diameter(60cm)
of Coil/Antenna
(The normalized
parameter)
 f : operating
Frequency (common)






Basic Theory


Non-linear Formula

Frequency Conversion and Modulation/Rectification

$$I = f(v) = aV + bV^2 + cV^3 \quad V = v_s(t) = V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t)$$

$$I(1st) = aV$$

$$I(2nd) = b v_s^2(t)$$


$$= \frac{1}{2} b \{ V_1^2 + V_2^2 + V_1^2 \cos(2\omega_1 t) + V_2^2 \cos(2\omega_2 t) + 2V_1 V_2 [\cos[(\omega_1 + \omega_2)t] - \cos[(\omega_1 - \omega_2)t]] \}$$

$$I(3rd) = cV^3$$

$$= \dots$$

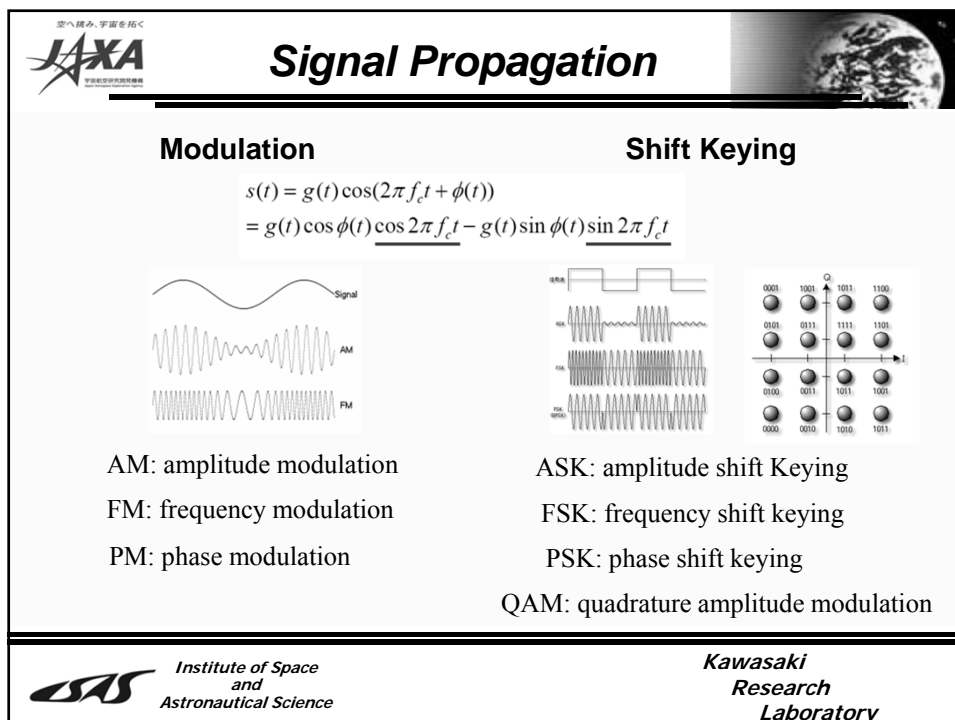
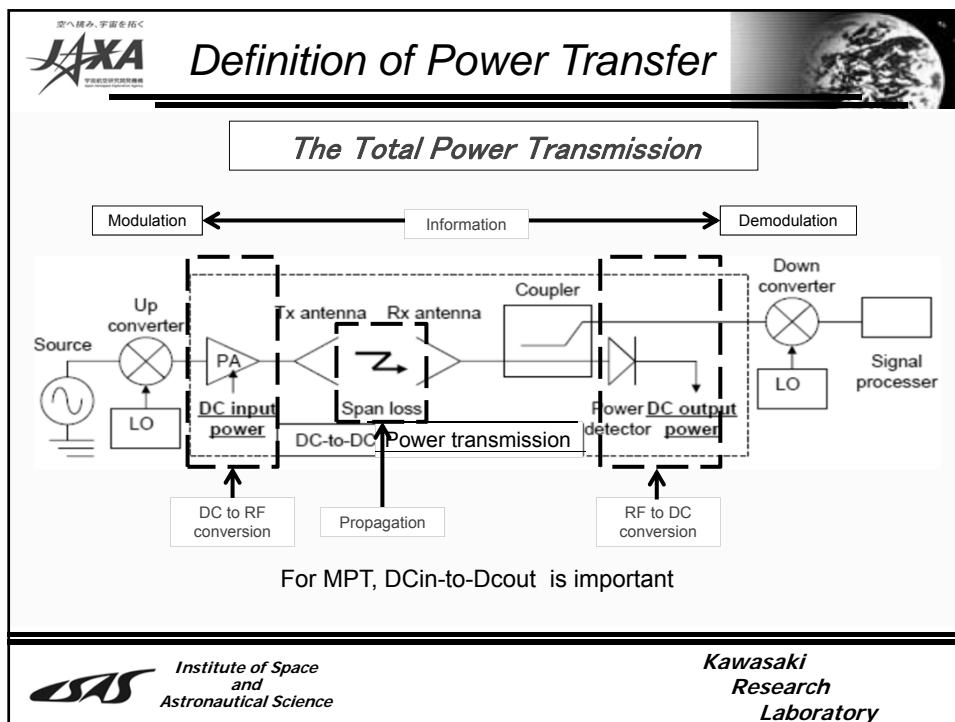
Carrier / Modulation

Harmonics
(Conversion
/Rectification)




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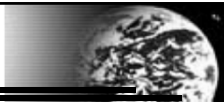
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The Microwave Components



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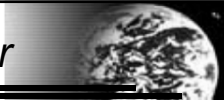
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Microwave Power Transfer



Expected MPT Technologies for the Green-Eco Technology

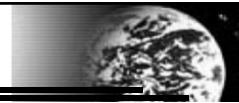
- Highly-Efficient, High-Power Circuit
 -> Green Energy Transmission
- High Efficient Rectifier
 -> Cost Effectiveness
- Active Integrated Antenna (AIA)
 -> Compactness
- Phased Array Antenna (APAA)
 -> Moving Target Tracking

Highly-Efficient, High-Power
Active Integrated Phased Array Antenna (AIPAA)



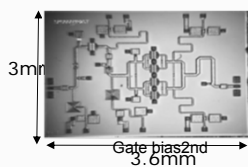
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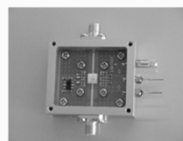


Microwave Communication and Power Transmission

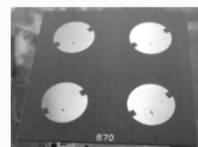
Overview of Devices, Circuits, MMICs and Antennas



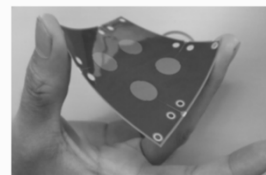
The C-band 2-stage MMIC power amplifier (25dBm)



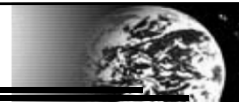
The Ku-band 3-stage MMIC low noise amplifier (NF=1.7dB) and the module



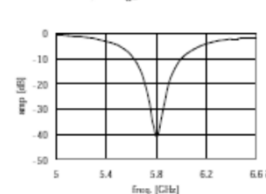
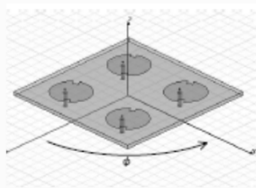
The 2x2 unit array



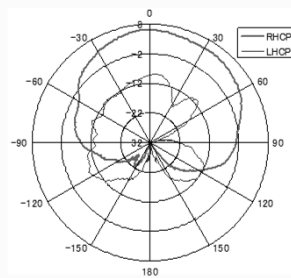
The printed antenna array



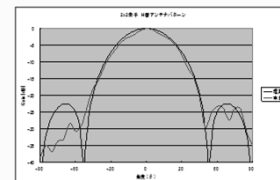
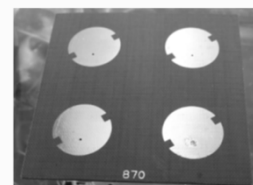
Antennas



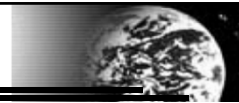
The calculated return loss



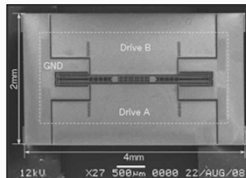
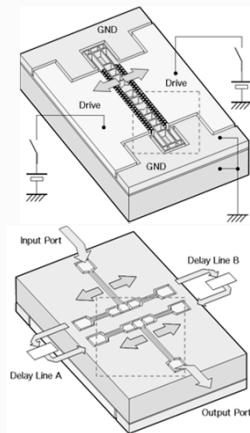
The single patch (Measured AP)



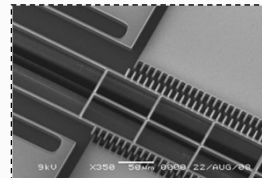
The 2x2 unit array



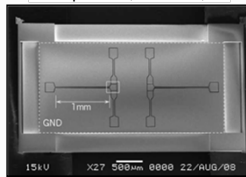
Ku-Band RF-MEMS (SPDT Switch)



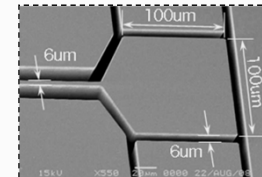
Top Side (Actuator)



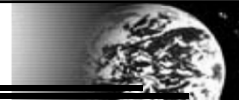
Actuator (zoomed)



Bottom Side (Movable Waveguide)

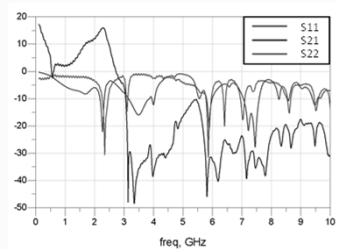


Contact Point



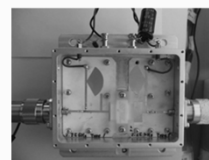
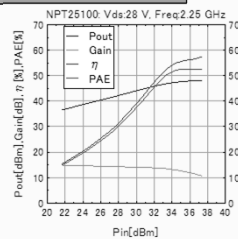
Microwave Communication and Power Transmission

100W-class GaN high power amplifier

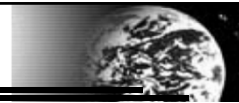


Characteristics

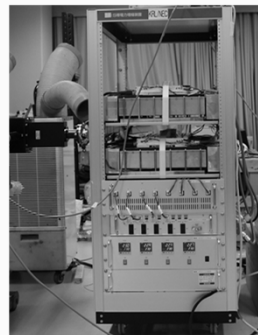
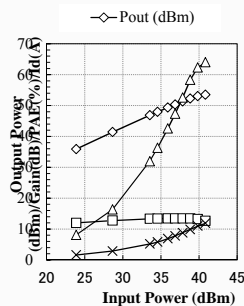
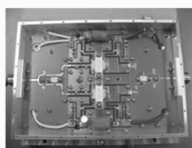
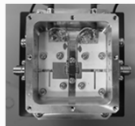
- S11 < -10 dB @2.2-2.3 GHz
- S21 > 15 dB @2.2-2.3 GHz
- P3dB: 48.0 dBm @2.25 GHz
- PAE (@P3dB): 52.6 % @2.25 GHz



Size: 100*76*30 mm³

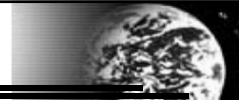


The Super-High Power Solid-State (GaN) Amplifier

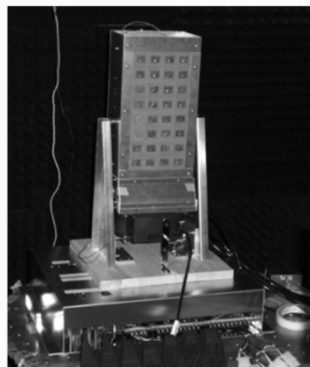


The SSPAs with GaN at S-band with 20W, 200 W, Efficiency of more than 50% and SS-Cooling

The 1kW GaN at S-band SSPA Combiner with about 90% Combining Efficiency, and with a Cooling System



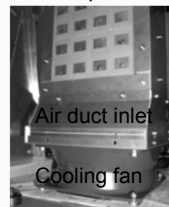
The High Power AIA Array



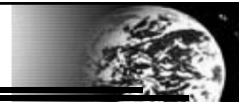
The 120W-output air-duct type of 32-element AIA Array



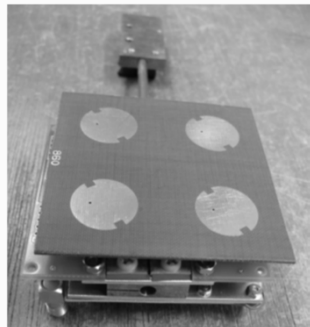
The top view



The cooling system



The 2x2 HPA AIA Unit Array with Heat Pipe

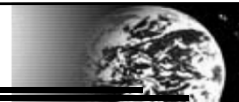


The Top View

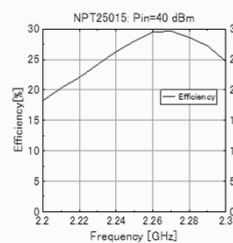
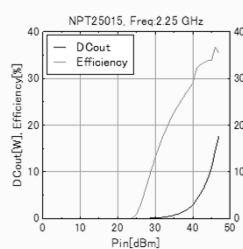


The Side View

Volume : 64mmx64mmx20mm



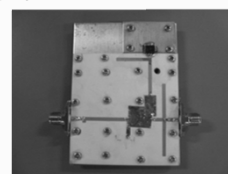
Microwave Communication / Power Transmission and Reception



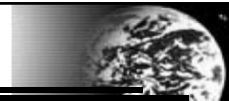
Characteristics

- Maximum DC output power: 17.8 W
- Maximum RF input power: 47 dBm
- Maximum conversion efficiency: 35.5 %

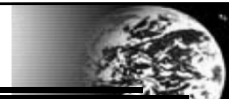
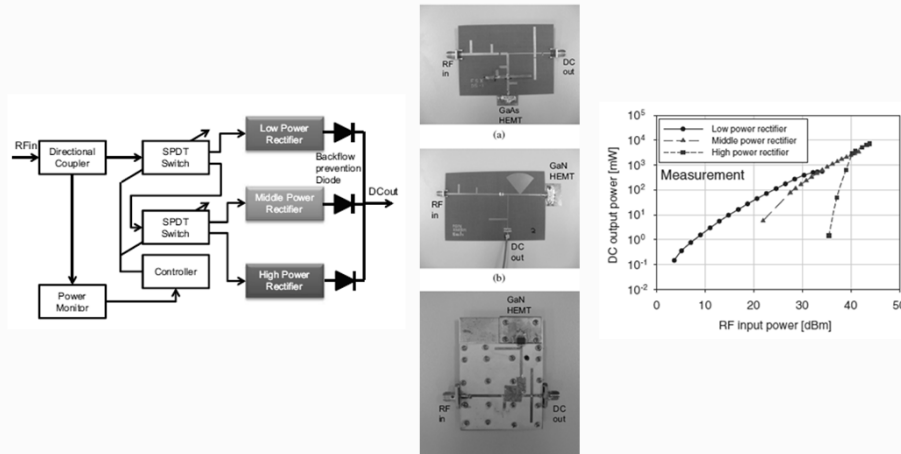
High output power characteristics are achieved.



Size : 50*70*5 mm³

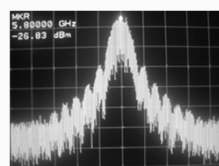


The Rectifier Unit with Wide Dynamic Range

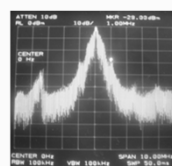


Microwave Communication / Power Transmission and Reception

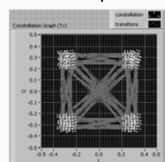
Modulation / Demodulation



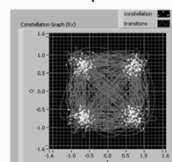
Tx Modulation Spectrum (MSK)



Rx Detector Spectrum (MSK)




Tx Spectrum (QPSK w/subcarrier)

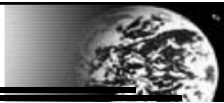


Rx Constellation (QPSK w/subcarrier)


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Compatibility of MPT



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Microwave Power Transmission



The Category of Microwave Power Transmission

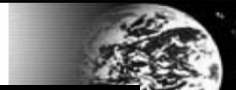
— **WiCoPT**
**Wireless Information/Communication and Power
Transmission**
(Effective use of the carrier with signal modulation)

— **WiSEnT**
Wireless Sensor and Energy Transfer
(Batteryless and energy harvest/scavenging)

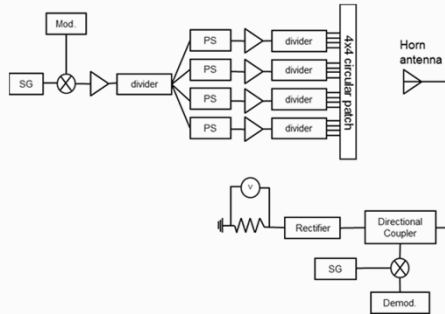


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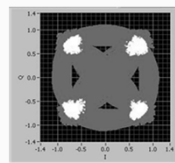
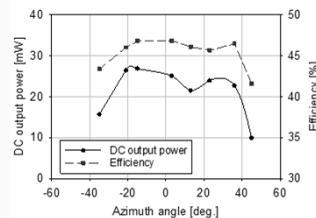
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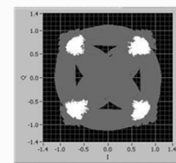
Microwave Communication / Power Transmission and Reception



Tx : 36 dBm@5.8 GHz
Distance : 1.0 m
Modulation-QPSK/1 Mbps
BER > 10E-5



(a) +35deg. Beam steering

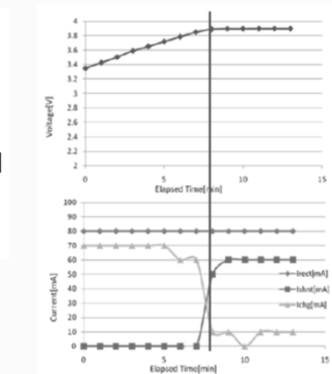
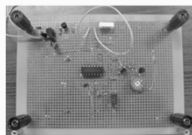
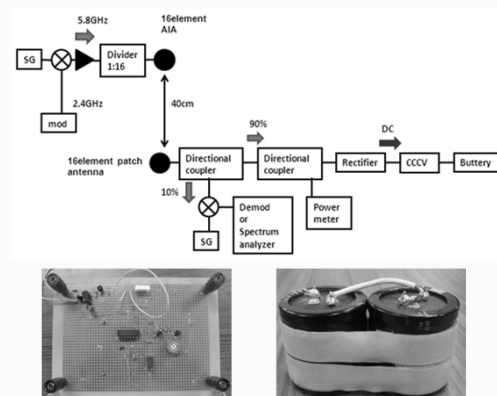


(b) -20deg. Beam steering

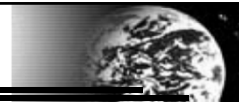


Microwave Communication / Power Transmission and Reception

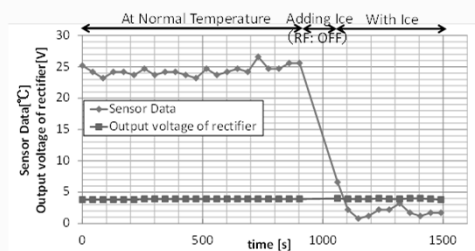
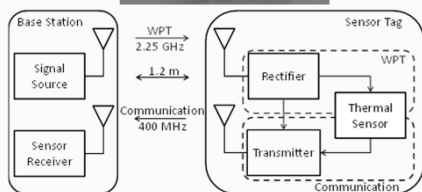
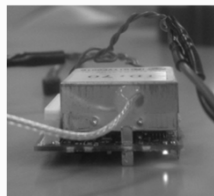
The Battery Charging (Receiving)



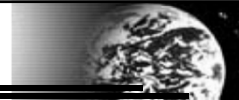
The battery charge-up histogram



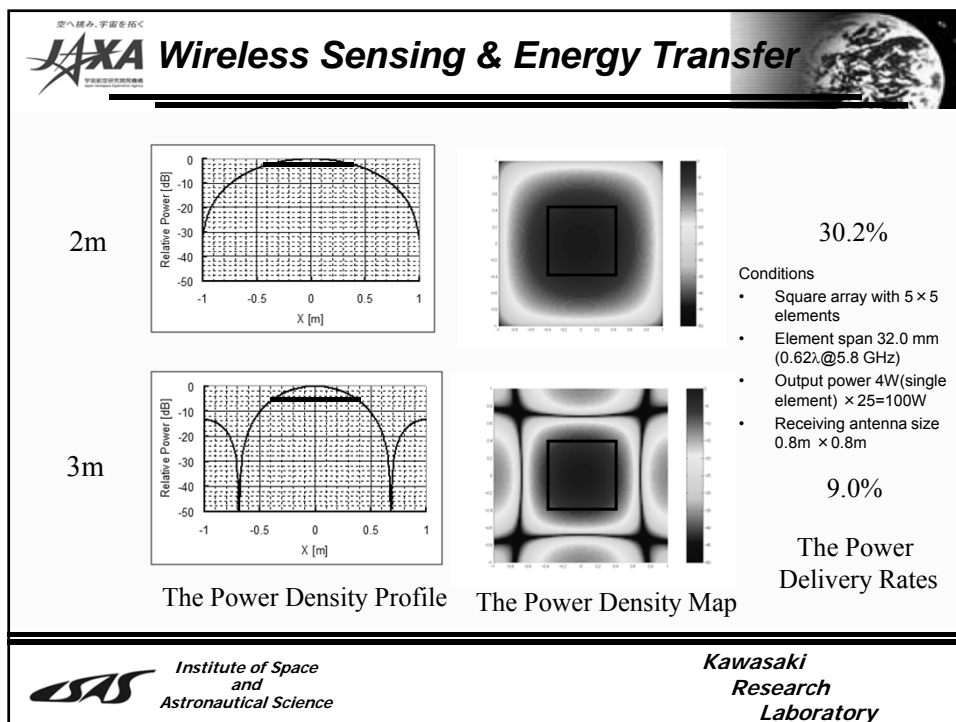
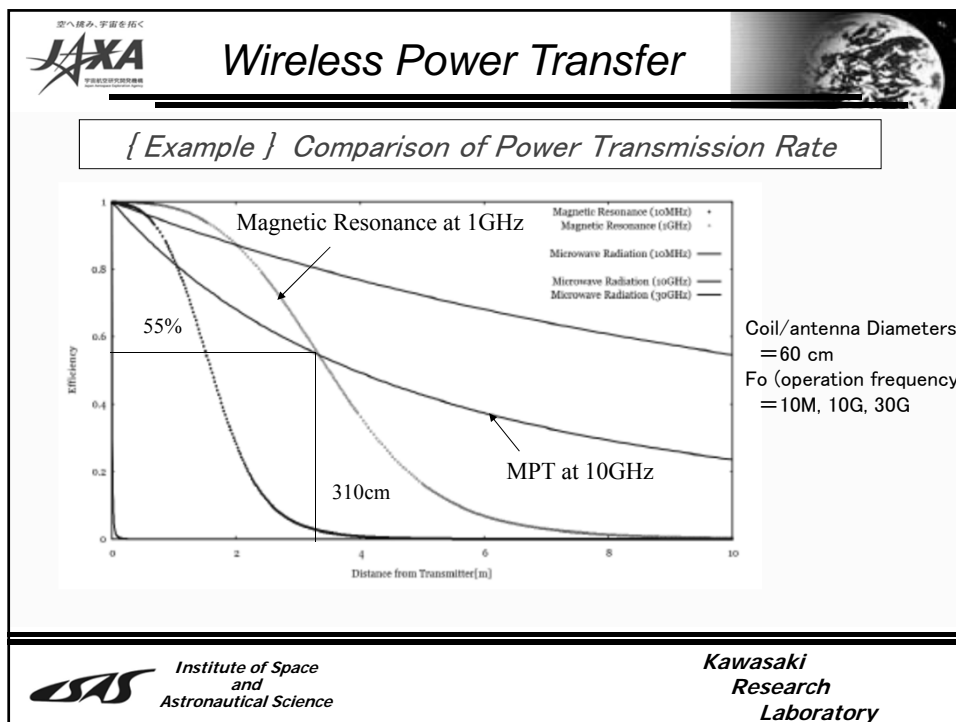
The Thermal Sensor Operation in WiSEnT



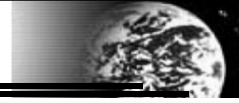
Normal operation of the sensor is confirmed in WiSEnT.



WPT Demonstration



WPT Test



Estimation of Power Delivery Rate

Conditions

- Square array with $5 \times 5 = 25$ elements
- Element span 32.0 mm (0.62λ @ 5.8 GHz)
- Output power 4W(single element) $\times 25 = 100W$
- Boundary of the far field $2D^2/\lambda = 0.99m$
- Receiving antenna size $0.8m \times 0.8m$

$$P.D. [W / m^2] = \frac{GtPt}{4\pi R^2}$$

Pt = 100W, Gt = 15dB(31.62)
2m : 62.9 [W/m²]
3m : 28.0 [W/m²]

Estimated receiving power (energy transfer rate)

2m : 62.9 [W/m²] $\times 0.75$ (constant : 0th-order approximation of directivity) $\times 0.64[m^2] = 30.2$ [W]
3m : 28.0 [W/m²] $\times 0.5$ (constant : 0th-order approximation of directivity) $\times 0.64[m^2] = 9.0$ [W]

Estimated energy conversion rate

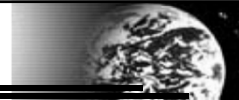
2m : 30 [W] $\times 0.4$ (RF to DC conversion) $\times 0.5$ (loss : 3 dB) = 6 [W]
3m : 9 [W] $\times 0.4$ (RF to DC conversion) $\times 0.5$ (loss : 3 dB) = 1.8 [W]



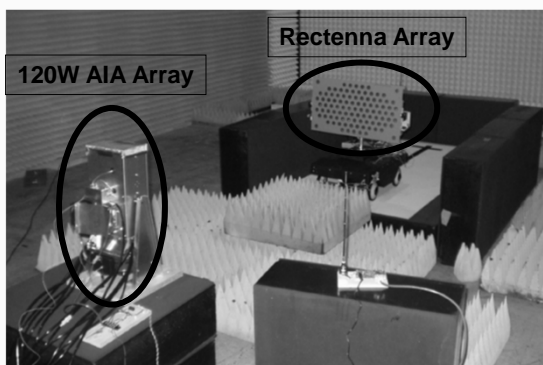
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Wireless Power Transfer

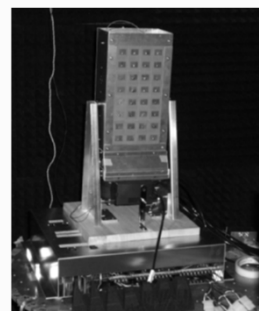


The 32-element 120W-output compact high power AIA array



The Rover Control Test

(The maximum requested power of the rover : 10W)



120W-output air-duct type
32-element AIA Array
(11cm thick / 4.0 kg w/o fan)



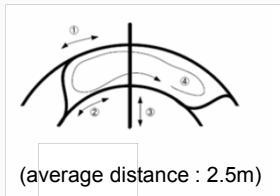
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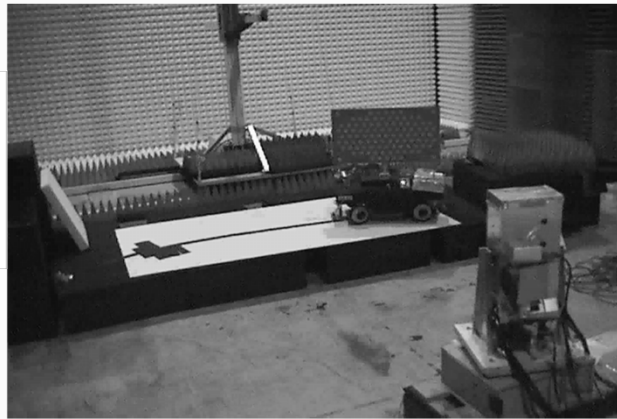
Wireless Power Transfer



The high power AIPAA for wireless power transmission



Rover motion of the test



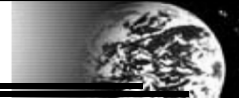
Rover Control Experiment



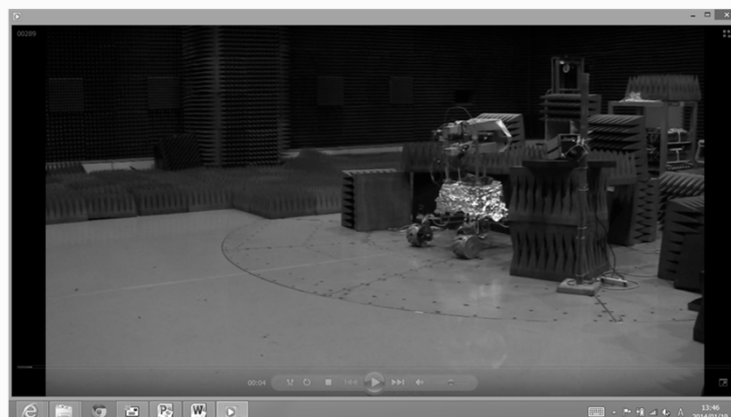
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WiCoPT Systems

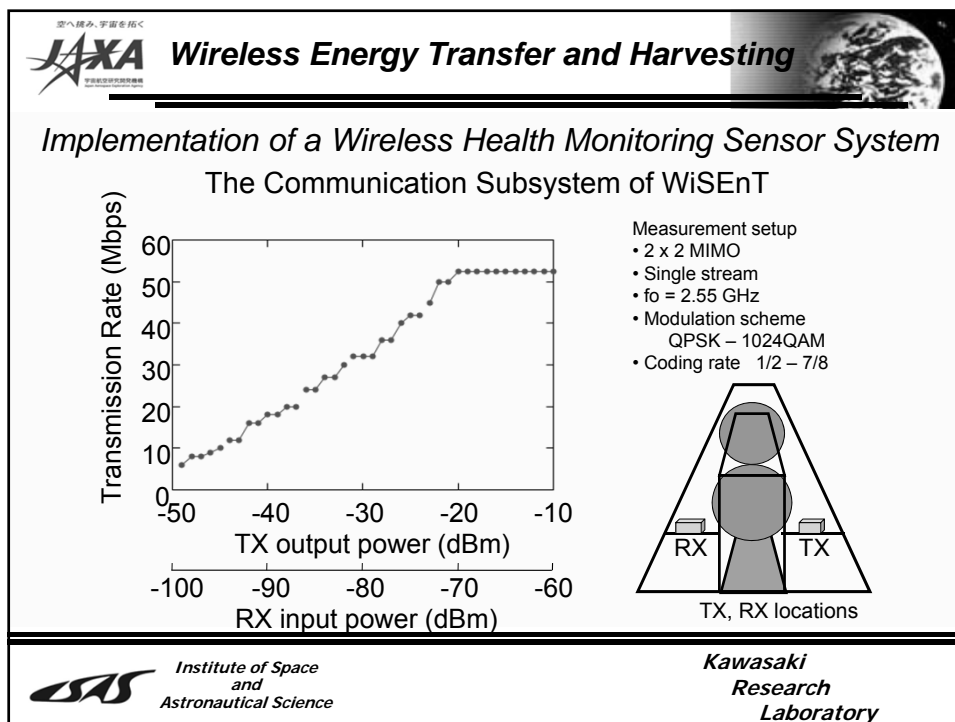
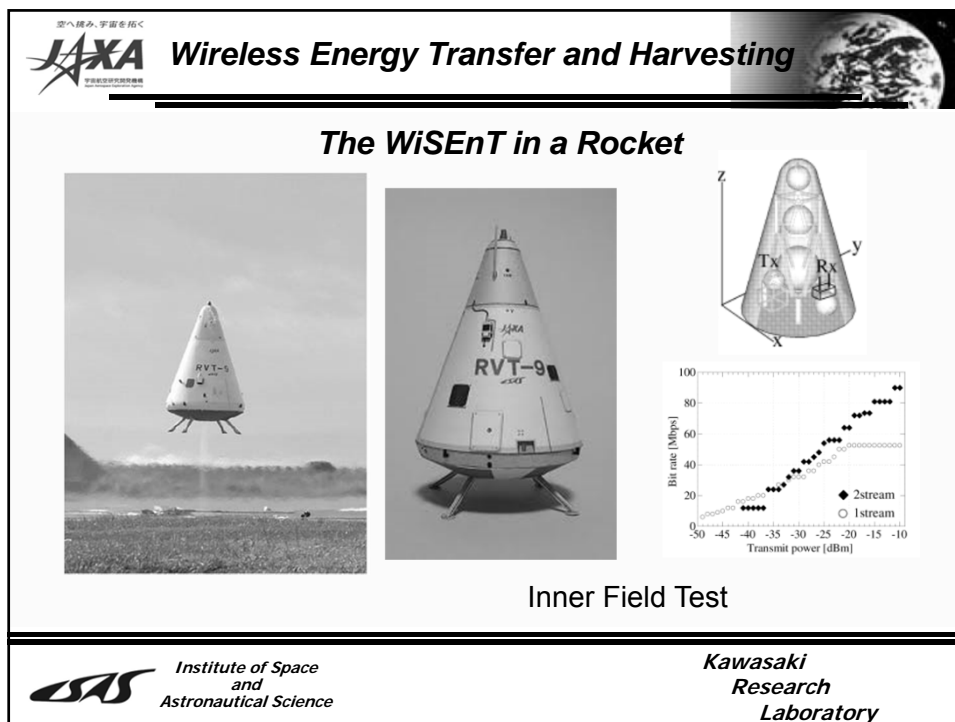


The hot-spot microwave power supply to a rover



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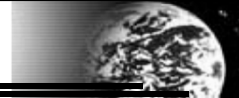
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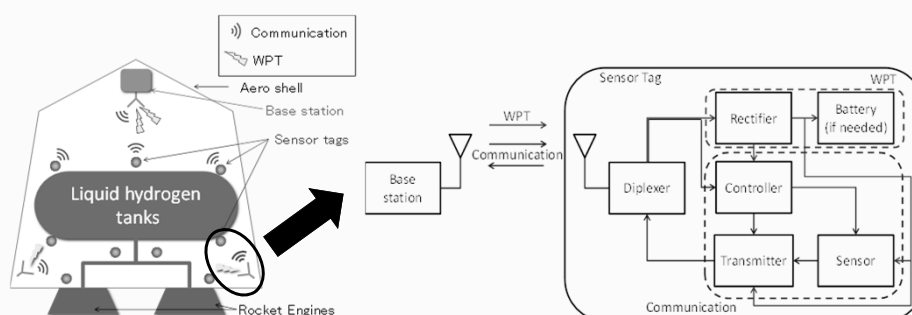


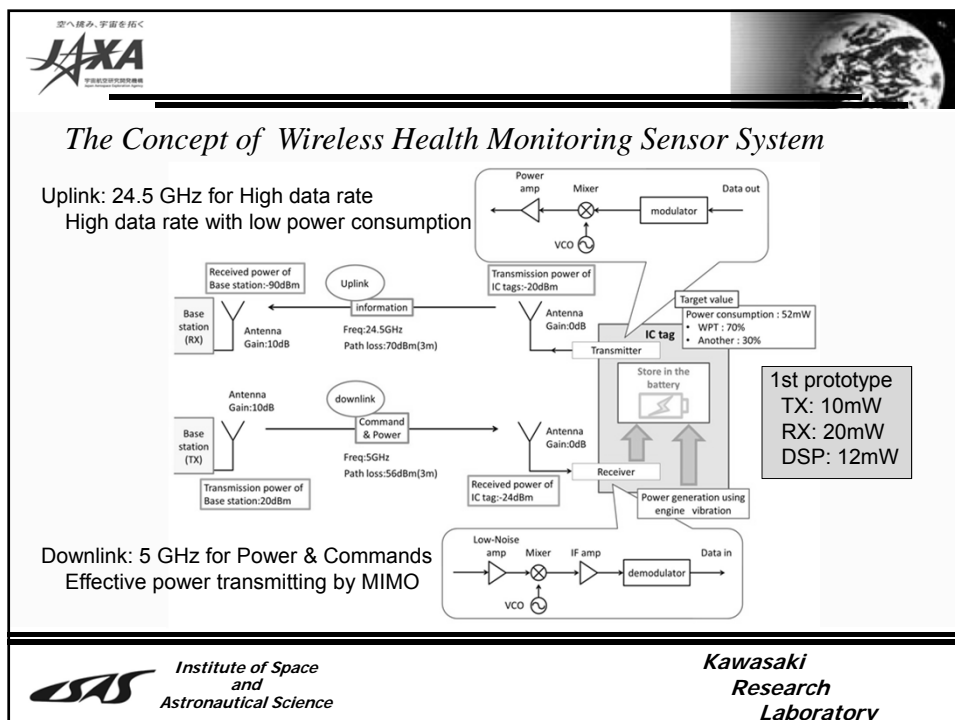
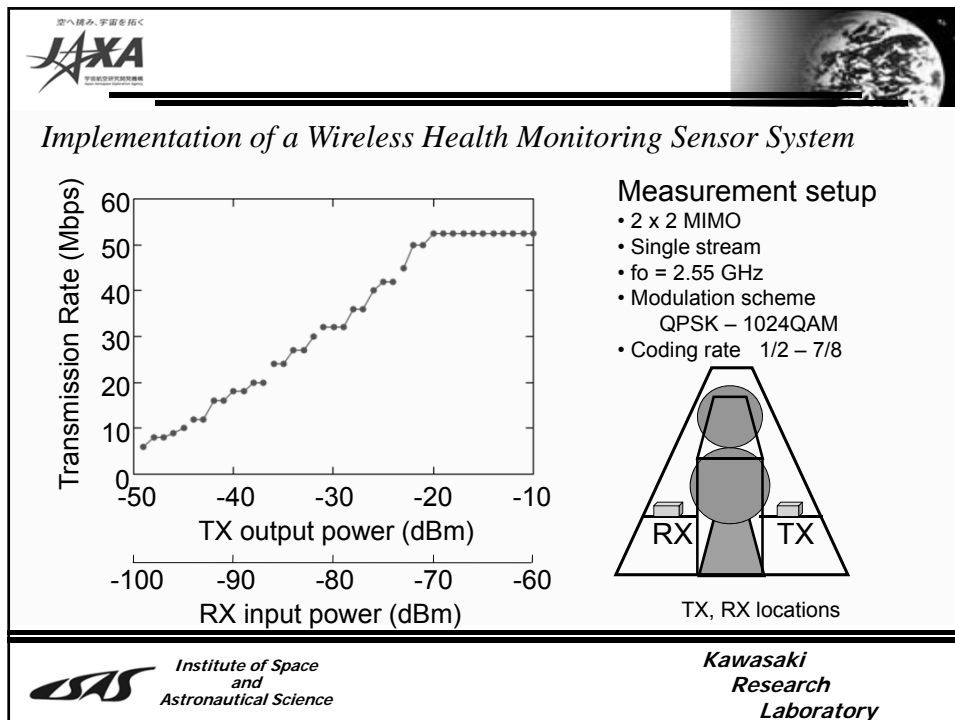
Implementation of a Wireless Health Monitoring Sensor System

- » Concept
 - > Use of microwaves for communication (command/ sensor data transmission) as well as for power supply (wireless power transfer: WPT)
- » Benefits
 - > Drastically removal of wire harness
 - > Equipment of sufficient numbers of sensor tags inside a spacecraft
 - > Compatibility with communication system inside of a spacecraft and that for up/down link




Implementation of a Wireless Health Monitoring Sensor System

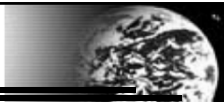





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宇宙航空研究開発機構
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Applications



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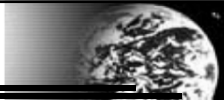
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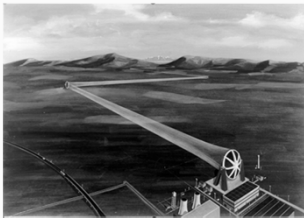


宇宙航空研究開発機構
JAXA


Applications




The Wireless Communication & Power Transmission



The Power Transmission
to the isolated island




The Rescue Robot



The Working Robot in Space

The Simultaneous Wireless Communication and Wireless Power Transfer



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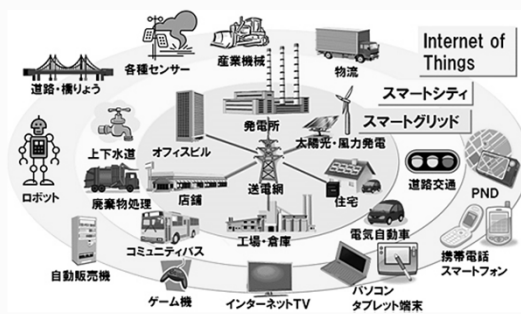
Applications



Internet of things by MPT (WiCoPT)



From EuMW (P2P -> M2M)



From NTT Data HP

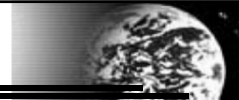
* Important Items : Number of IP, Security, **Electric Power Source**



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Conclusions

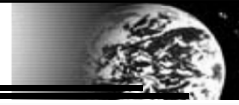


- The Wireless Green-Eco Technologies by microwave technology and the category of WPT & EH were introduced.
- The components and high power transmitter AIA array for the microwave WPT and the AIPAA and the rectenna array were fabricated.
- The compatibility of MPT with communication and MPT were demonstrated.
- Many applications of MPT in a wireless sensor network are expected to be realized.



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Thank you very much