IRIS PROJECT: SPACE SOLAR POWER

Mason Nixon
Austin Scheidemantel
Andrew Punnoose
Diapa Sanogo
Tri Pho

Aut viam inveniam aut faciam
"I will either find a way or make one"
To Power The World!

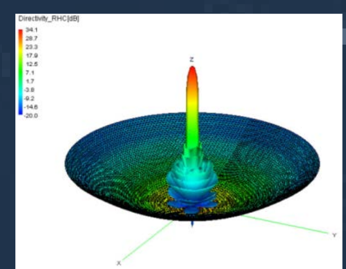
Earth Station Collector and Rectenna

Antenna Design

Primary Considerations

1. Gain Pattern
2. Center frequency (24.125GHz)
3. Bandwidth
4. Polarization – Circular
5. Beam taper
6. Sidelobe restriction

(Must also describe Beamwidth (HPBW), Sidelobe level/Front-to-Back Ratio, Radiation Resistance, Max Rated Power, VSWR)



Antenna Features

Cassegrain-fed Architecture
Min. Subreflector Diameter = 0.249m (20λ)
Circularly Polarized

Dish Antenna Trade-off

$D_1 D_2 = \lambda r$
Assuming D_2 (in the sky) = 100m,
D_1 = ((3e8/24.125e9)*20.2e6)/100 = 2.512e3m
r= 20.2e6m (worst case for MEO)

Array of Antenna Circuits

- Each Rectenna circuit can produce an output between 3 and 10Kw per square meter DC power using monolithic rectennas as our approach in rectifying the received microwave power. This is not enough for our overall generation of DC power for the earth power grid.
- We need to put multiple rectenna circuits together to create an array of rectenna circuits.
- 100000 to 333333.33 square meter rectenna array would be enough to produce at least 1GW of electric power and deliver it to the Earth power grid.

$$\textit{Microwave Power Reveiced by Each Rectenna} = \frac{\textit{Total Intercepted Microwave Power by Dish Antenna}}{N}$$

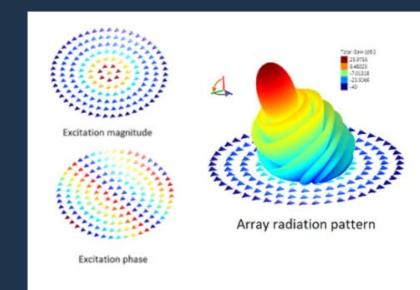
- The DC to DC power conversion can achieved with a total possible efficiency of 76%. This can efficiency result can be expected if a good matching of components can be realized

Array shape: Circular

Element spacing, d = (1900/2π)*λ = 3.75m
Element excitation amplitude – fixed amplitude for steering
Element excitation phase – varies on desired direction
Array element pattern

Array Elements

element diameter, D = 300m
dish depth, d = 25m
f (focal length) = (D^2/16d) = 225m,
f/D = 0.75,
elements in array = 10

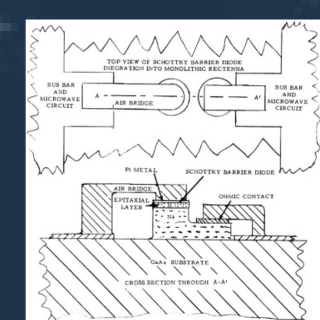


Other Parameters

By the pattern multiplication theorem:
Array pattern = Array element pattern x Array factor(AF)
Array diameter = 2,512 km
Beamforming: MMSE (Minimum Mean Square Error)
Total Losses
Friis Transmission:
$P_r = P_t + G_t + G_r + 20 \log(\lambda / 4\pi) - 20 \log(r)$ - Other Losses
Other losses = 9.6dB
$\mathbf{P_r = 6.251}$ **GW**
Electrical Efficiency: 76%
Delivered Baseload Power: 4.75 GW

Approach in Rectenna Circuit Design

- The Collector dish on Earth will need a front-end circuit which will be able to convert microwave power to DC power. This is the purpose of the rectenna circuit which will receive the microwave power through the collector dish. The overall system is composed of the collector dish and the rectenna circuit is called the rectenna
- At 24.125GHz, we will use a monolithic approach in which the diodes and all the circuitry are built on a Gallium Arsenide (GaAs) substrate which we know can function at frequencies above 250GHz.



Satellites

Orbit Design

The orbits chosen for this mission are two Borealis orbits and a high altitude circular orbit. The inclination and angle of these three orbits were tuned such that the orbits are sun synchronous. A sun synchronous orbit maintains its angle with respect to the Sun, meaning that the solar panels will always point towards the Sun without a need for active control (disregarding perturbations). The Borealis orbit was chosen for its high ellipticity that allows for long periods of coverage of the Northern hemisphere. The circular orbit was chosen to cover the ground stations located in the Southern Hemisphere. Each orbit contains four satellites, for a total of twelve satellites. Shown below is a table of the orbit parameters.

Orbit	Long. of Asc. Node (deg)	Perigee Altitude (km)	Apogee Altitude (km)	Inclination (deg)	Arg. of Perigee (deg)
Borealis 1	0	633	7605	116.6	270
Borealis 2	180	633	7605	116.6	270
Circular	131	5486	5486	150	0

Subsystems

Power

The power transmitted to ground stations is gathered using thin film solar panels with an efficiency of at least 16.8 kW/kg. At this efficiency, 595,000 kg of solar panels must be used to generate the desired 10 GW. Accounting for a 15% degradation in efficiency every 5 years, a total of 700,000 kg of solar panels must be launched initially, and approximately 105,000 kg of solar panels must be replaced every 5 years.

Stationkeeping

In order to maintain desired orbits, stationkeeping maneuvers must be performed. These maneuvers will be performed using a chemical thruster, requiring approximately 10,200 kg of fuel annually. This fuel will be provided through periodic fuel resupply missions.

Thermal

The thermal conditioning system will consist of passive coatings placed on the rear of the solar panels, allowing the solar panels to radiate excess heat to maintain operating temperatures. The main body of the satellite will perform thermal conditioning through the use of active heat piping.

ADACs

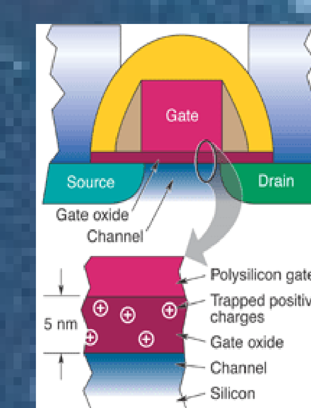
Magnetoplasmadynamic thrusters were chosen to provide attitude control, due to the need to constantly maintain the orientation of the solar panels towards the Sun. These thrusters, while expensive, provide high levels of thrust (relative to other electric thrusters) and are extremely efficient.

Star tracker (left) and Sun sensor (right) (from www.spaceyuga.com)

The Space Environment

- Micrometeorite Environment
- Rad Environment & Effects On Hardware
- Impact On Mission and Reliability

Impact crater in Aluminum
Source: NASA Reference Publication 1408, "Meteoroids and Orbital Effects On Spacecraft."

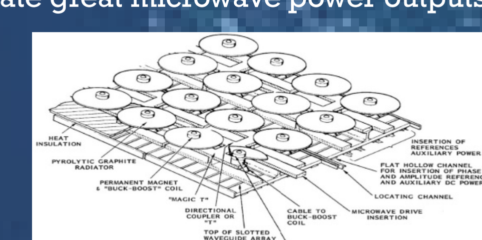


Cross section of an NMOS transistor showing the gate oxide and conducting channel formed between the source and drain. The trapped charges shown in the inset are responsible for failure.

Microwave Power Hardware

Magnetron Directional Amplifier (MDA)

- A microwave device is needed to convert the collected DC power from the photovoltaics cells to RF microwave power. This is done through a Magnetron Directional Amplifier (MDA).
- The MDA is composed of a conventional magnetron (similar to what is used in microwave ovens) with the addition of a passive directional device (a ferrite circulator or a "magic –T"), the output sensors and compensators for both amplitude and phase tracking, and the feedback control circuits.
- As each MDA has a limit in how much DC power it can intake, multiple MDAs can be put together to form an array of MDAs. This is called a power module.
- The power module is composed of four radiating units. In turn, each radiating unit is composed of two MDAs.
- The power module can generate great microwave power outputs; in the order of GW of power.



Benefits of MDA

- Phase and amplitude tracking capability of magnetron directional amplifier.
- Exceptionally high signal to noise ratio
- Long life based because of low operating temperature of the carburized thoriated tungsten cathode.

Communications

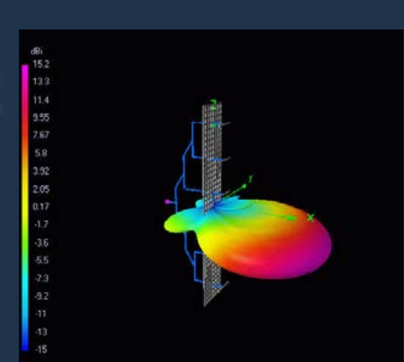
Designed with security in mind – protection from interception, jamming, spoofing

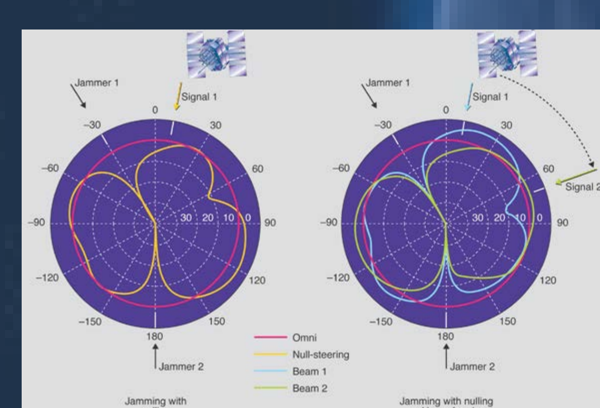
Table C1. Communications Sub-System Overview
Modulation Scheme
0.125 GMSK-FH
Carrier Frequency
Uplink 44 Ghz Downlink 20 Ghz
Occupied Bandwidth
Uplink 500 Mhz Downlink 500 Mhz
Uncoded Data Rate
2.0 Mbps
Coding
Rate 1/2 Turbo Coded
Data Security
ECDSA-384

Satellite-side Physical Hardware

Phased-element Array Antennas

- Fast pointing due to electronic steering
- Capable of shaping the antenna gain pattern dynamically. (Shown below on the left)
- Useful for casting a null in the gain pattern where an attempted jamming signal is detected (Shown below on the right)

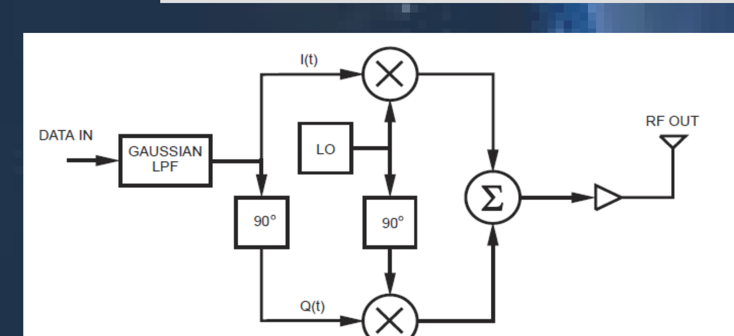




Modulation Specifications

Gaussian Minimum Shift Keying – Frequency Hopped – BT 1/8

- GMSK used for efficient spectral bandwidth and independence from power amplifier linearity
- Frequency hopping used for interception obfuscation
- A coherent GMSK modulator is shown to the right



Transport Layer Encryption

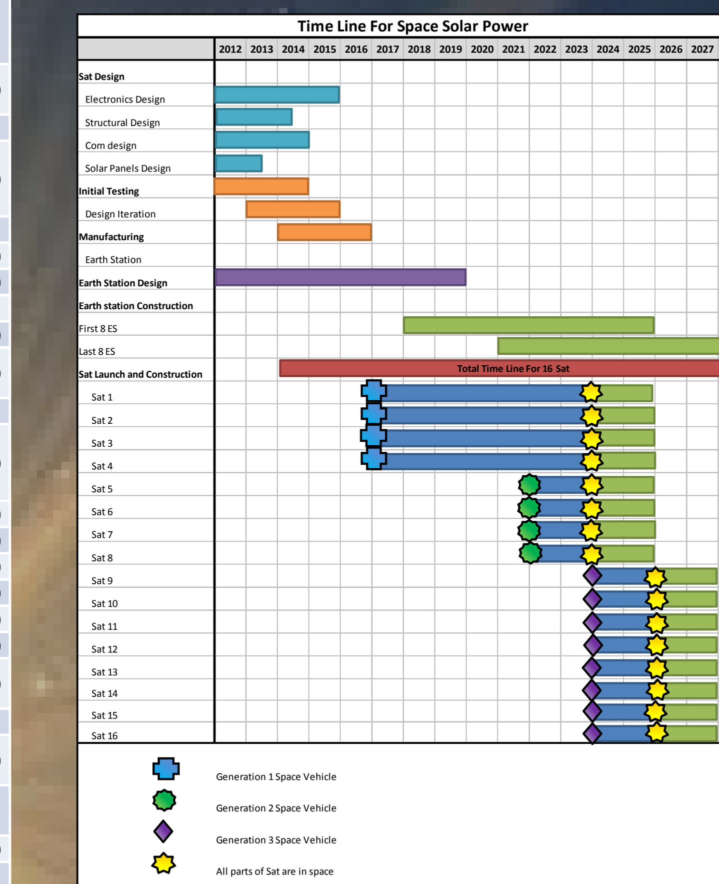
384-bit Elliptic Curve Digital Signature Algorithm

- A step up from the currently recommended 256-bit ECSDA encryption for level SECRET information

Budget And Logistics

Estimated Budget for 16 SSPS and Earth Stations	weight in (Kg)	material cost	man hour cost including building
Main Power transmitting dish	186,000	$10,000,000	$35,000,000
Electronics			
Electronics for satellite systems other then com and power tx	30	$2,500,000	$15,000,000
Communications dishes			
RX Dish and Components	50	$350,000	$1,250,000
TX dish components	50	$450,000	$1,750,000
Structural			
Support Structure	125	$550,000	$1,200,000
Extra Structural Protection form Micro meteorites	25	$50,000	$350,000
Power Generation			
Solar Panels	6,000,000	$1,829,473,810	$2,500,000
Added solar panels to account for deterioration	105,000		
Power Cabling	100	$3,500,000	$1,500,000
Antenna Probe	11	$1,200,000	$480,000
Copper Vanes	44	$750,000	$300,000
Copper Shell	45	$890,000	$356,000
Ceramics	30	$400,000	$160,000
Filament	8	$340,000	$136,000
Magnetic Circuit Including SM Co Magnets	266	$3,500,000	$1,400,000
Phase Control			
Voice Coil and Inductive Tuner	64	$650,000	$260,000
Amplitude Control Power Conditioning			
Buck-Boost Coil	200	$1,300,000	$520,000
Cooling			
Pyrographite Radiator	350	$4,500,000	$1,800,000
Thermal	446	$350,000	$1,000,000
Stationkeeping	10,213	$350,000	$1,000,000
Attitude Control	55,125	$1,500,000	$50,160,561
Transverse fuel	4,900	$350,000	$550,000
2 Robot builder Arm	100	$425,000	$1,200,000
Total Mass (Kg)	6,363,080.94	→Convert into Mass in lbs	13,998,778
Cost to build Without launch Cost	$1,976,251,370		
Average Launch Cost per satellite see attached table requires all 16 satellites to be launched to achieve pricing	$2,550,000,000.00		
Extra Maintenance Cost Per Sat	$12,000,000.00		
Total cost per satellite	$4,538,251,370		
Total cost for 16 satellites	$72,612,021,923		
1 Earth station costs (including all Rx dishes)		$100,000,000	$26,000,000
Total Earth station costs (including all Rx dishes)		$1,600,000,000.00	$416,000,000.00
Producing 1 GW per station total return possibility			
16 Satellites	$74,628,021,922.66	$672,555,700,899	
32 Satellites	$40,000,000,000.00	$1,345,111,401,799	
16 Satellites	$74.63	$672.56	In Billions
32 Satellites	$40.00	$1,345.11	In Billions
Producing 4.75 GW per station total return possibility			
16 Satellites	$74,628,021,922.66	$3,194,639,562,277	
32 Satellites	$40,000,000,000.00	$6,389,279,124,554	
16 Satellites	$74.63	$3,194.64	In Billions
32 Satellites	$40.00	$6,389.28	In Billions
	Only Delivery 1GW	With our Solution and Efficiency Delivering 4.75GW per station	
Rate of Return (ROI) X times investment Original investment	9.0	42.8	
If 16 more sat and earth stations were added	17.6	159.7	
Rate of Return (ROI) in %	901%	4281%	
If 16 more sat and earth stations were added in %	1760%	15973%	

Time Line For Satellite Launch



Launch Costing and Scheduling

Cost Schedule for Space Launches		Flights per year	Total lbs Launched	lbs left to get to space	Cost
Generation 1 Year 1	1st year	20	400,000.00	111,590,225	1,200,000,000.00
	2nd year	20	400,000.00	111,190,225	1,200,000,000.00
	3rd year	20	400,000.00	110,790,225	1,200,000,000.00
	4th year	20	400,000.00	110,390,225	1,200,000,000.00
	5th year	20	400,000.00	109,990,225	1,200,000,000.00
Generation 2 year 1	6th year	100	2,000,000.00	107,990,225	2,000,000,000.00
	7th year	200	4,000,000.00	103,990,225	4,000,000,000.00
	8th year	400	8,000,000.00	95,990,225	8,000,000,000.00
	9th year	800	16,000,000.00	79,990,225	4,800,000,000.00
Generation 3 year 1	10th year	3200	64,000,000.00	15,990,225	6,400,000,000.00
	11th year	3200	64,000,000.00	63,980,449	3,200,000,000.00
	12th year	3200	64,000,000.00	-19,551	6,400,000,000.00

Solar Panel Cost

Cost for Solar Panels	
Power per	16.8 KW/Kg
Total Power (MW)	160,000 MW
Cost per Watt from Ken Zweibel, NREL	$0.19
Total Cost Per Sat	$1,829,473,809.52

Added Cost and Weight From Space Hardening

Estimated added weight, Time, and Manufacturing Cost For long Term Space Solar Power Reliability				
Percent weight Increase By Considering				
	Rad		Micro Meteorites	
	Weight Increase	Devolvement Cost Increase	Weight Increase	Devolvement Cost Increase
Electronics	7-23%	60-120%	0-3%	3-7%
Solar Cells	1-3%	3-7%	4-7%	3-6%
Satellite Structure	0-2%	13%	17%	23%