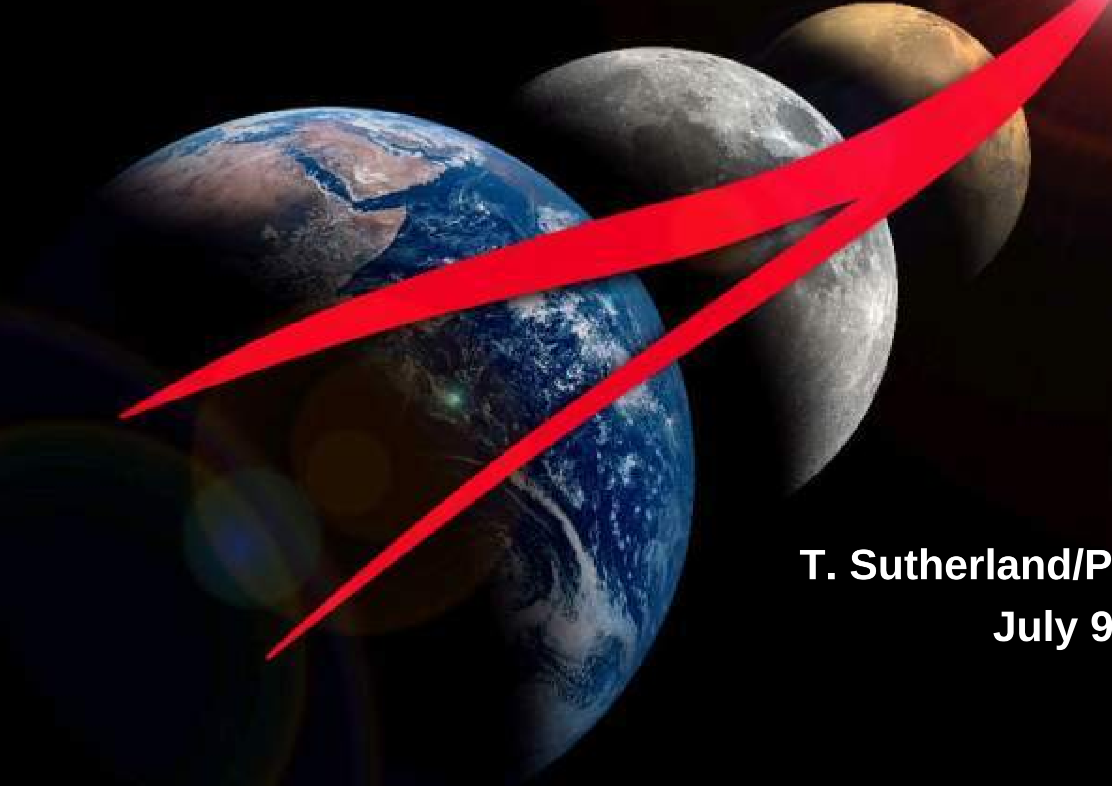
16.89J / ESD.352J Space Systems Engineering
Spring 2007

Massachusetts Institute of Technology
ATA-01-1003 – Lunar Telescope Facility
IDAC3 Results Presentation to the CxAWG



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July 9, 2007

CONSTELLATION

Project Description

To:

Deliver value to the astronomy community *and* add value to the proposed lunar exploration program

By:

Leveraging the lunar exploration architecture and enabling unique or better astronomical observations

Using:

An astronomical observatory located in cislunar space

Image of a lunar observatory, removed due to copyright restrictions

Contributors

- Professors Ed Crawley and Olivier de Weck
- Dr. Massimo Stiavelli, Professors Jackie Hewitt and Jeffrey Hoffman, Dr. Tupper Hyde, Dr. Gary Mosier, Sarah Shull, Mark Baldesarra, and Thomas Coffee
- MIT graduate research team: Mark Avnet, Gautier Brunet, Justin Colson, Phillip Cunio, Tamer Elkholy, Bryan Gardner, Takuto Ishimatsu, Richard Jones, Jim Keller, Zahra Khan, Ryan Odegard, Jeff Pasqual, Jaime Ramirez, Timothy Sutherland, Chris Tracy, Chris Williams

Approach

- **Methods Used:**
  - Stakeholder analysis
  - Concept enumeration and downselection
    - Multiple parallel studies and rigorous methodologies
    - Done in the context of existing and proposed telescope designs
  - Detailed concept design
    - Lunar and free-space options were considered
- **Tools and Models Used:**
  - LIRA integrated telescope modeling tool
    - *In-house design (similar to ICEMaker)*
    - *Excel-based*
  - *Pugh rankings*
  - *Morphological matrices*
- **Significant deviations from the original intent of the baselined TDS**
  - Two telescope designs were carried to completion, instead of one

Results Summary

- **Stakeholder Analysis Results**
  - Stakeholder value-delivery network model
  - Assessment of most important loop in the network
- **Concept Generation and Downselection Results**
  - Two detailed telescope designs
  - LIRA (Lunar Interferometric Radio Array)
  - LIMIT (Lunar Infrared Modular Interferometric Telescope)
- **Detailed Concept Design Results**
  - Lunar surface uniquely enables capabilities
  - Potential human deployment and servicing schemes

Stakeholder and Value Flow Identification and Ranking

Importance	Major Stakeholders
5	Scientists NASA Congress
4	Executive Telescope Operator
3	Contractors U.S. People
2	Media Educators International Partners
1	

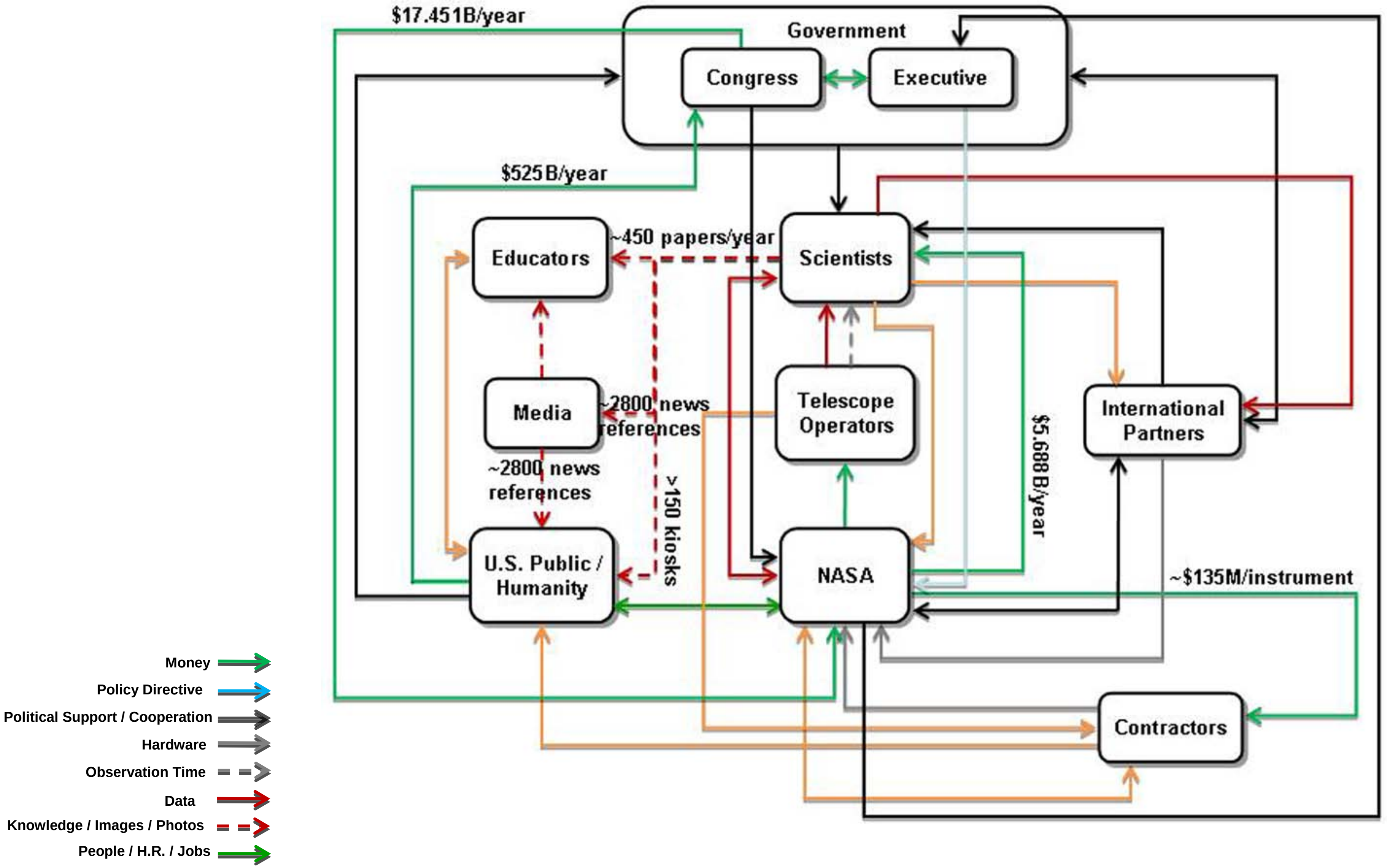
Type of Flow		a	b	c	d	e	f	g	h	i	j
Educators	a	a	K	H	K						
Media	b		b		K						
U.S. Public/Humanity	c	H	K	c	K			H			H
Scientists	d				d	S	S		S	D,O	$,D
Congress	e			$,S		e	$		S		
Executive	f			S		$	f		S		S
Contractors	g							g		H	$,H
International Partners	h				D,H	S	S		h		S
Telescope Operator	i									i	$
NASA	j			H	D,H	$,S	P	H,I	S,I		j

Key	
$	Money
P	Policy Directive
S	Political Support
I	Instruments, Hardware
O	Observing Time
D	Data
H	Human Resources
K	Knowledge, Images, Pictures

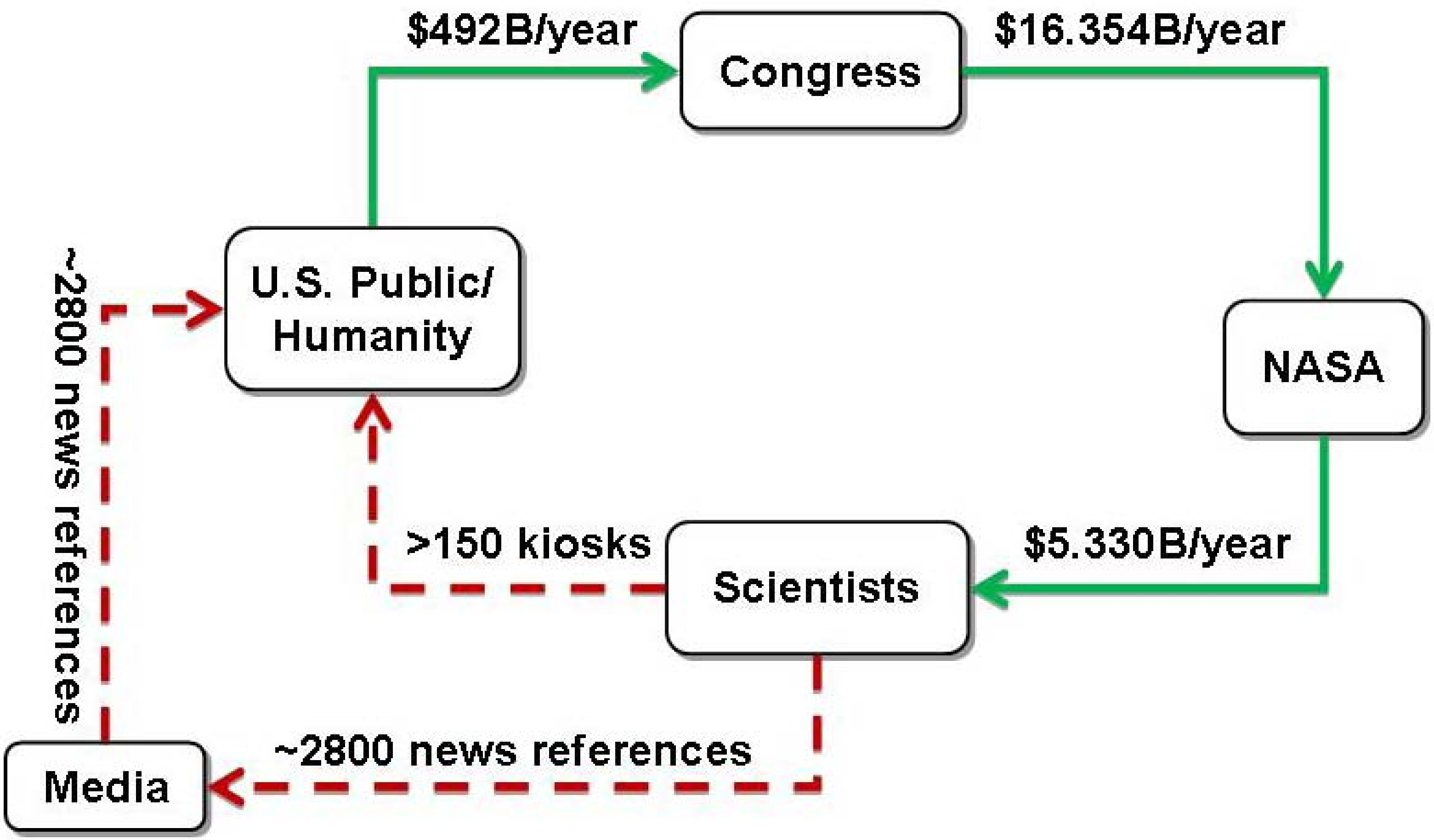
Key	
5	Essential
4	Very Important
3	Important
2	Somewhat Important
1	Helpful
0	Irrelevant

- **Knowledge, Images, and Pictures**
  - Scientists → Educators: ~450 papers/year (HST)
  - Scientists → Media: ~2800 news references (HST)
  - Media → Public: ~2800 news references (HST)
  - Media → Educators: ~2800 news references (HST)
  - Scientists → Public: >150 science museum kiosks (HST)
- **Money**
  - Public → Congress: $492 billion/year (2007 non-defense discretionary budget)
  - Congress → NASA: $16.354 billion/year (2007 NASA budget)
  - NASA → Scientists: $5.330 billion/year (2007 NASA science budget)
  - NASA → Contractors: $132 million/instrument (HST, in 2007 USD)

Stakeholder Flow Network Model



Most Important Loop in the Network



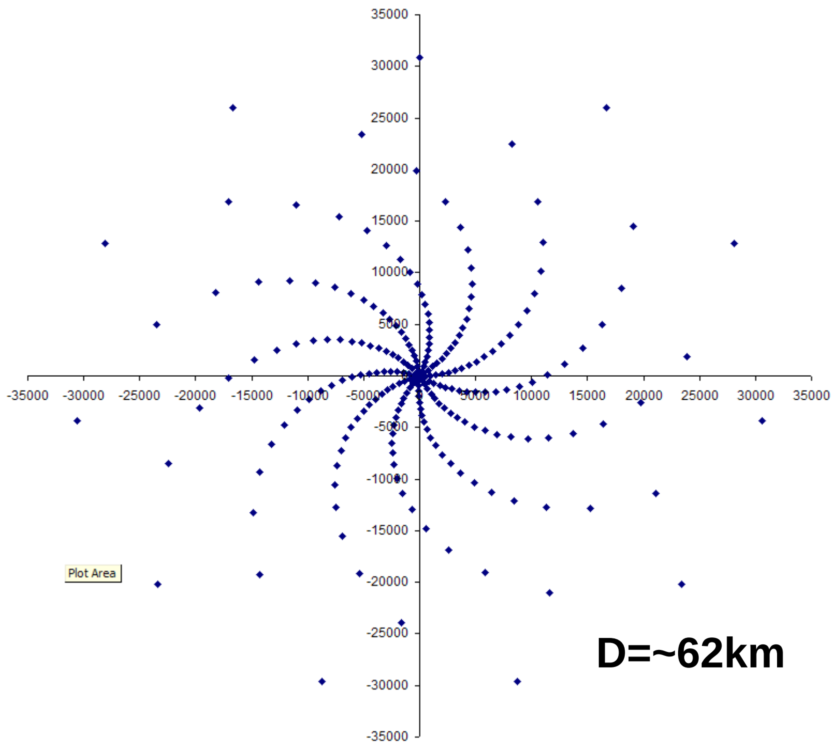
Money (based on 2007 budget figures)

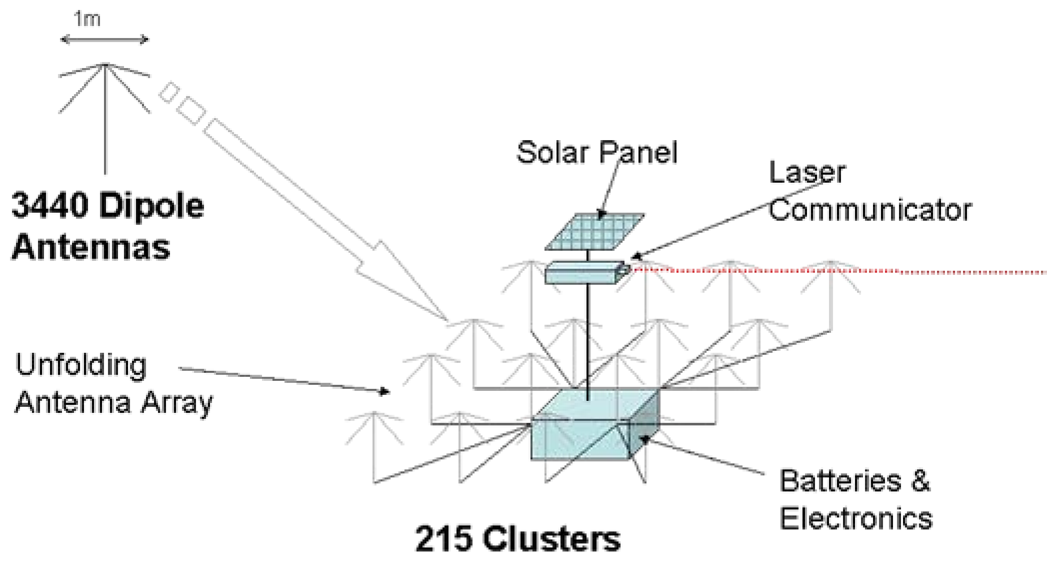
Knowledge/Images/Photos (based on Hubble Space Telescope)

Recreating the Hubble Loop

- Successfully brought together science and human spaceflight communities
- Unprecedented scientific output – over 4,000 published papers
- Intense public interest – over 2,800 news references
- Strong support from Congress
- 5th human servicing mission in September 2008 will extend Hubble's lifetime through 2013
- Recreating this loop requires generating knowledge, images, and photos for public consumption in key areas of scientific interest, such as the Epoch of Reionization or Planet and Star Formation

Lunar Interferometric Radio Array





- 3440 dipole antennas separated into 215 clusters (16 per cluster)
- Clusters distributed in 62 km diameter array
- Data transmitted to central processing unit
- Central unit processes raw data in real time (14Gbps)
- Refined data transmitted via relay system to lunar limb for transmission to Earth
- Laser communication systems used throughout to avoid radio pollution of Moon's far side

LIRA RF Attenuation on Lunar Far Side

- **Epoch of Reionization**
  - The birth of the first stars and galaxies as the universe emerges from the cosmic "dark ages"
  - Can be observed by the turnoff of redshifted 21-cm radio emission from neutral hydrogen as the universe becomes ionized
  - Instrument design will be driven by sensitivity/FOV to observe the EOR
- **Extrasolar Planets**
  - Emission from charged particle interactions with planet's magnetospheres
- **Solar Science and Particle Acceleration**
  - Low frequency radio emission from particle acceleration sites in the inner heliosphere
- **Serendipitous science**
- **Preliminary location chosen at 5º past limb**
  - Numerical simulation at 50 kHz
  - Actual measurements required for future work
- **Operates at radio frequencies below those possible from Earth**

$$\text{Sensitivity} = \frac{2k_B T_{sys}}{A\eta N^2} \cdot \frac{1}{\sqrt{\Delta\nu \cdot \tau}}$$

$A = \text{Antenna Collecting Area} \sim \lambda^2$

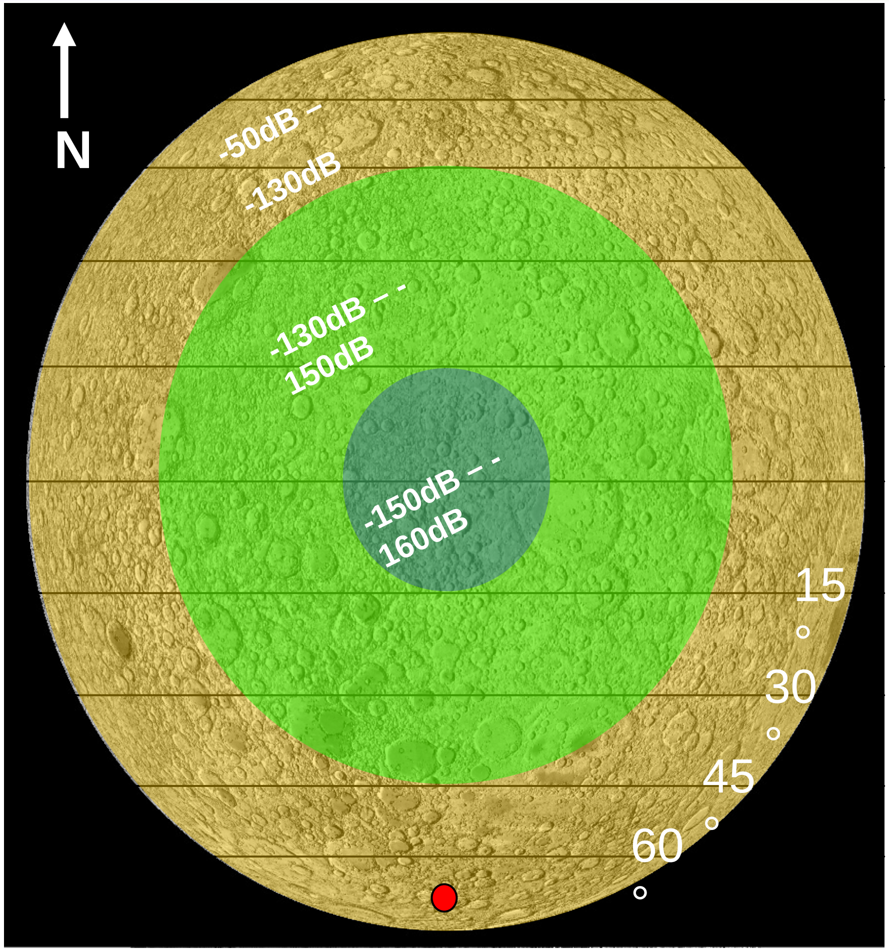
$\eta = \text{Antenna Efficiency}$

$N = \text{Number of Dipoles}$

$\Delta\nu = \text{Bandwidth (instantaneous)}$

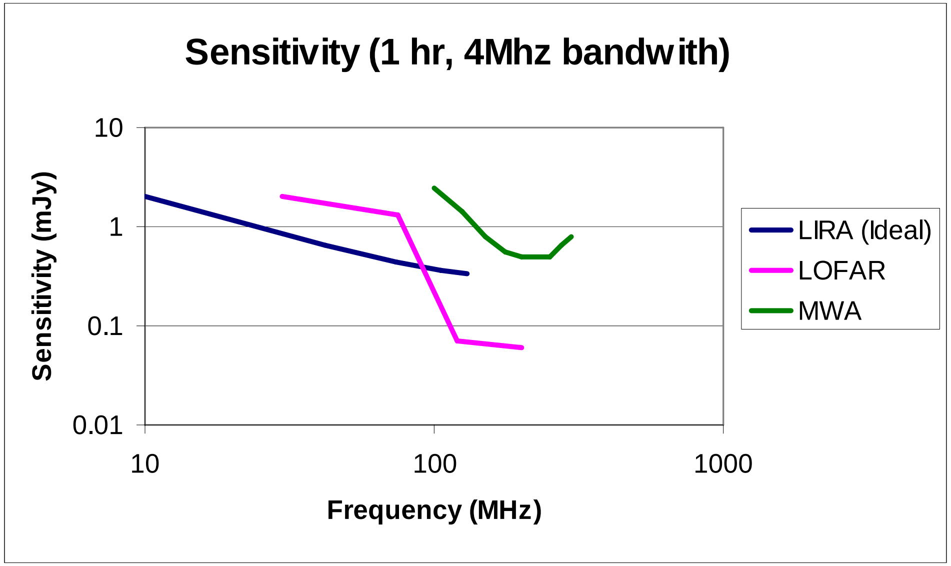
$\tau = \text{Integration Time}$

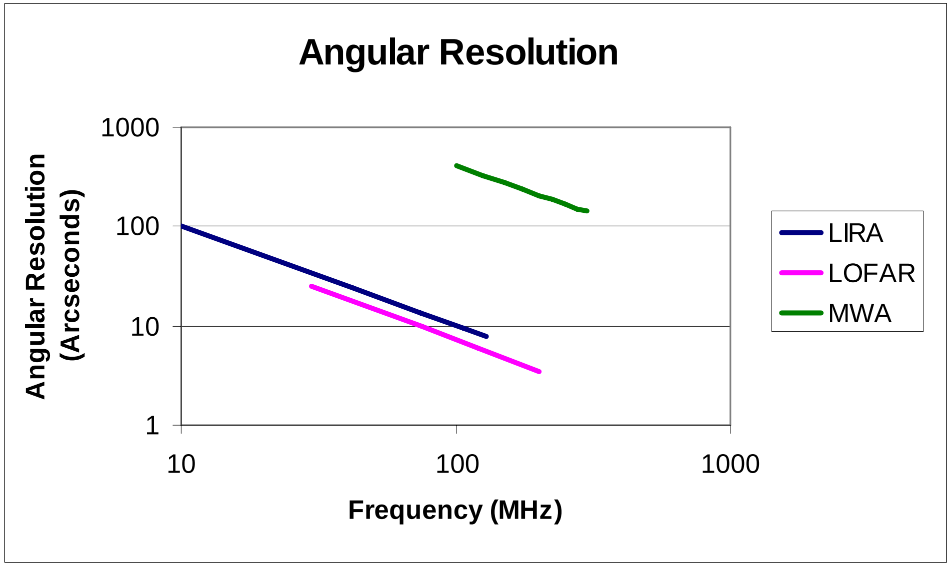
$T_{sys} = \text{System Temperature} = T_{Sky} + T_{Inst}$



LIRA Sensitivity and Resolution Comparisons

- The sensitivity for LIRA is idealized (frequency independent, uniform efficiency)
- No current high resolution systems go below 30 MHz





Optimized Characteristics

- Frequency Range: 10 to 130 MHz
- Number of Dipoles: 3440
- Array Diameter: 62 km
- Bandwidth: 32 kHz
- Number of Clusters: 215

Optimized Capabilities

- EOR Resolution: 15 arcminutes
- Sensitivity: 2.0 mJy at 10 MHz, 0.3 mJy at 130 MHz
- Max Resolution: 7.7 arcsec (at 130 MHz)
- FOV Diameter: > 25 degrees at all freqs

LIRA Cost Estimation

Subsystem Mass and Cost Estimation		
	Mass (kg)	Component Cost (M$)
Electronics	58.2	28.2
Communications	826.7	6.5
Power	4546.1	1.7
Structures and Mechanisms	7149.5	71.5
Deployment	1007.3	256.6
Integration and Other	3396.9	91.1
Software and Ground Segment	--	270.7
Subsystem Total	16,984.5	726.2

Transportation Cost			
	Cost/Ares V (M$/Launch)	Number of Launches Required	Cost (M$)
Transportation	1260	1	1260
Total			1,260

Total Cost – $1.987 Billion

LIMIT Telescope Facility

Lunar Infrared Modular Interferometric Telescope

- ♦ **Science Goals**
  - Galaxy and Star Formation
  - Brown Dwarfs
  - Active Galactic Nuclei
  - Detection and Formation of Planets
  - NIR Weak Lensing Survey

- ♦ **NIR/FIR Golay-9 array with 0.85 m elements**
  - Telescope elements based on Spitzer design
  - Operationally tested instruments and optics
- ♦ **Modular design is flexible and upgradeable to Golay-12 or Golay-15**
- ♦ **Located on Shackleton Crater floor**
- ♦ **Benefits from the lunar surface**
  - Avoids the atmospheric opacity in the infrared
  - Thermally stable shadowed environment
  - Surface enables precisely fixed interferometeric baselines
  - Serviceable by astronauts

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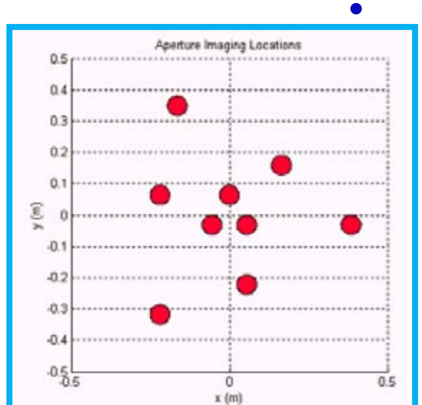
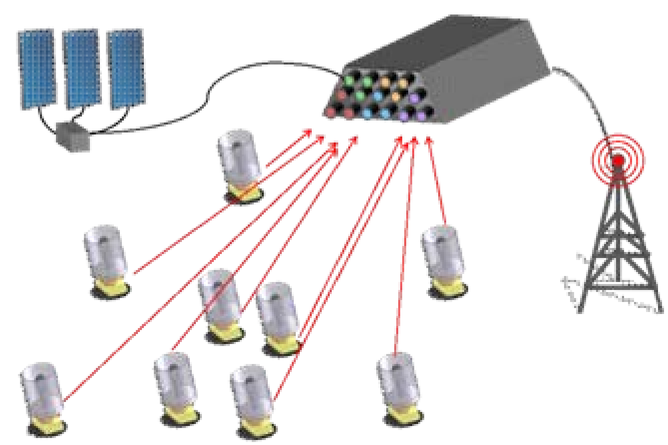
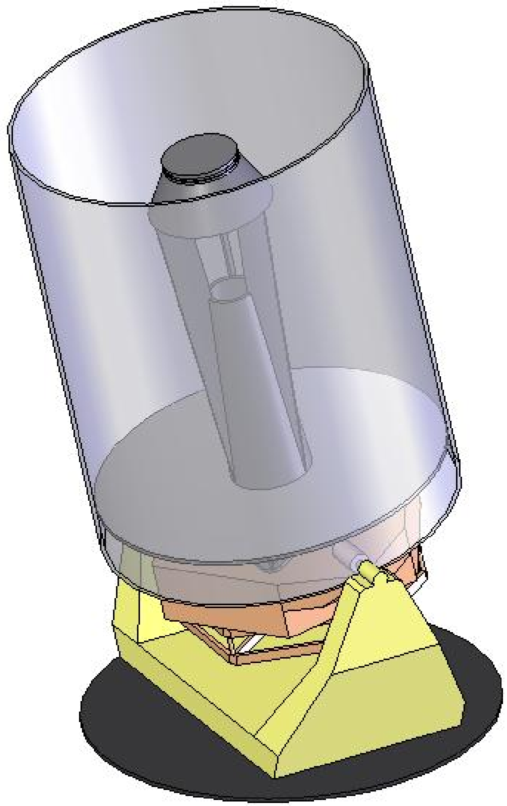
Bussey, D. B. J., et al. "Illumination conditions at the lunar south pole." ***2001 IEEE Aerospace Conference Proceedings*****, 2001, vol.3 p. 1187-1190**



[2] Miller, D.W., "Adaptive Reconnaissance Golay-3 Optical Satellite", http://ocw.mit.edu



LIMIT Collecting Instrument and Structure



♦ Spitzer-Derived IR Telescope

- 85 cm diameter primary, f/12, 50 kg
- Solid beryllium piece, aluminum coated mirrors
- Ritchey-Chrétien design

♦ Outer Shell

- 1 meter diameter, 2 meters tall
- Aluminum honeycomb and yoke structure, base is 23.5 kg

♦ Beam Collimator to Direct Light

- Similar to VLT-I
- Developed via research on high-efficiency IR fiber optics

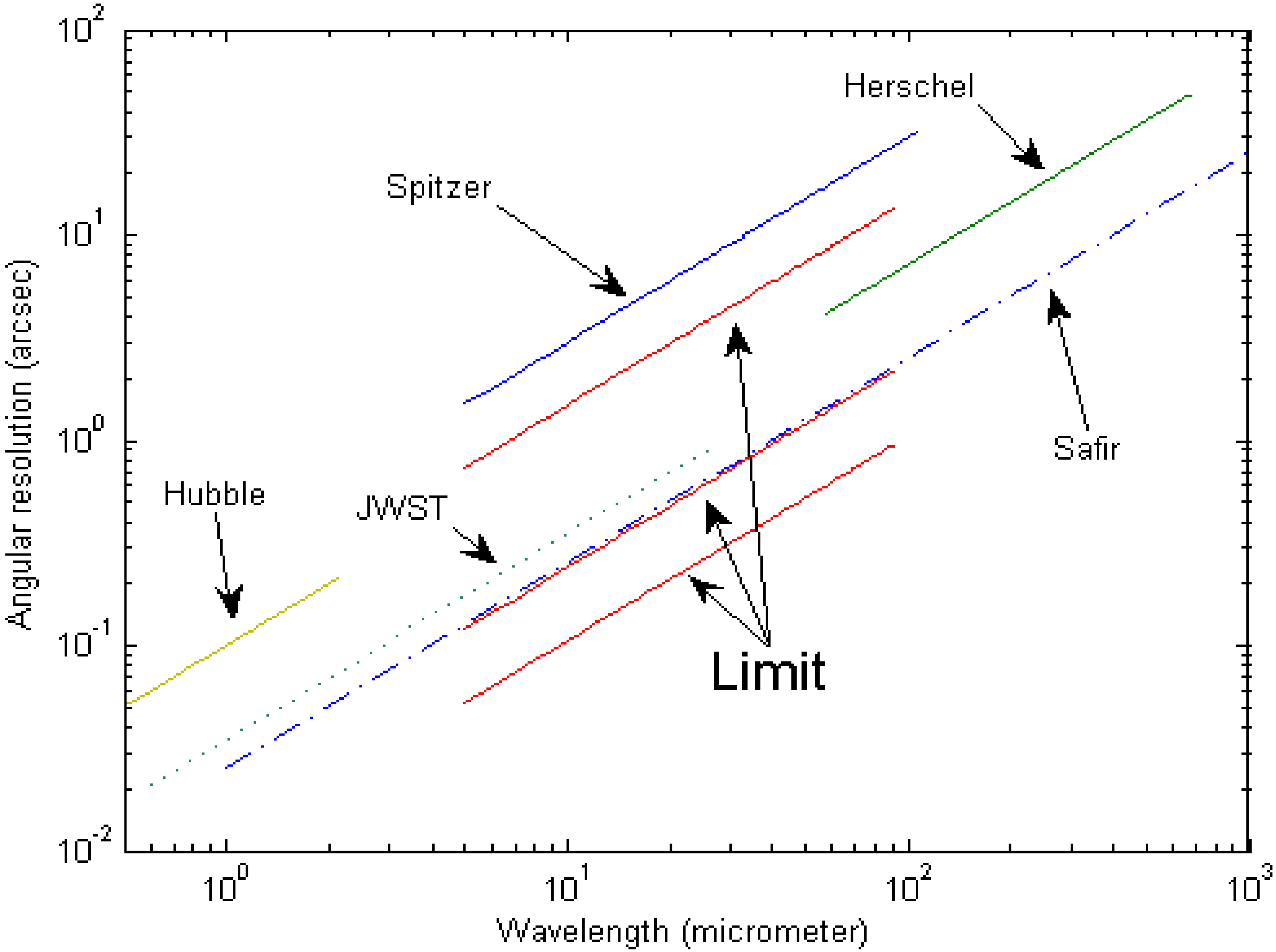
♦ Range : 3.5 – 180μm

- I-IRAC: 256x256 Imaging InSb and Si:As. 3.5, 4.5, 6.3, 8, 10μm
- I-IRS: 128x128 Imaging and spectroscopy Si:As/Sb.
- I-MIPS: 128x128 Si:Sb, Ge:Ga detectors.

♦ Power

- Solar panel array on the southern rim of Shackleton Crater, mounted on a sun tracking base
- 2.75 kW beginning of life, 2.25 kW end of life (10 yrs)
- Staggered shadows gives effective 90% sunlight
- Modular expandable base of batteries located near panels
- 10 km power cable to telescope array

LIMIT Concept Comparison



LIMIT Cost Estimation

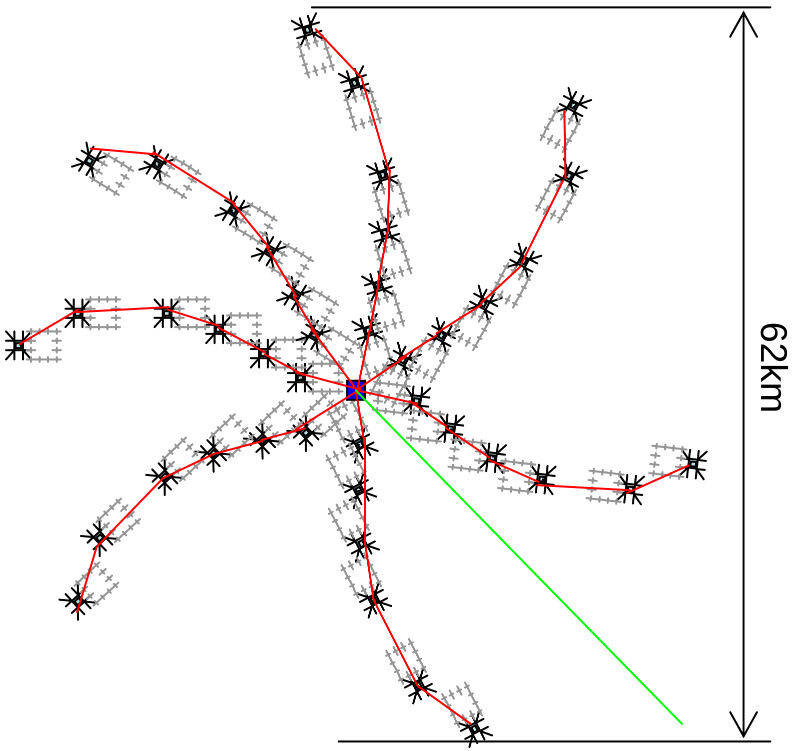
Subsystem Mass and Cost Estimation		
	Mass (kg)	Component Cost (M$)
Telescopes (9)	1027	45.1
External Optics	429	5.8
Structures and Mechanisms	212	2.9
Active Thermal Control	40	0.1
Electronics	10	4.7
Communications	13	0.2
Power	1789	0.3
Integration and Other	880	14.8
Subsystem Research & Development	--	977.8
Ground Segment Development	--	270.7
Total	4,399 (kg)	1322 (M$)

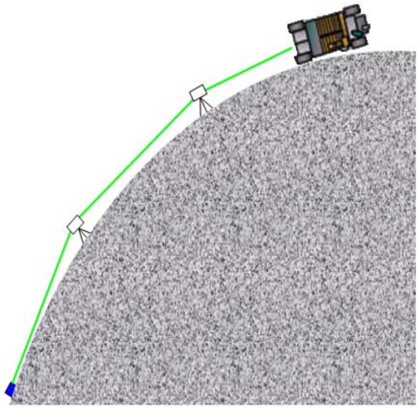
Transportation Cost			
	Cost/Ares V (M$/Launch)	Number of Launches Required	Cost (M$)
Transportation	1260	~0.25	308
Total			308 (M$)

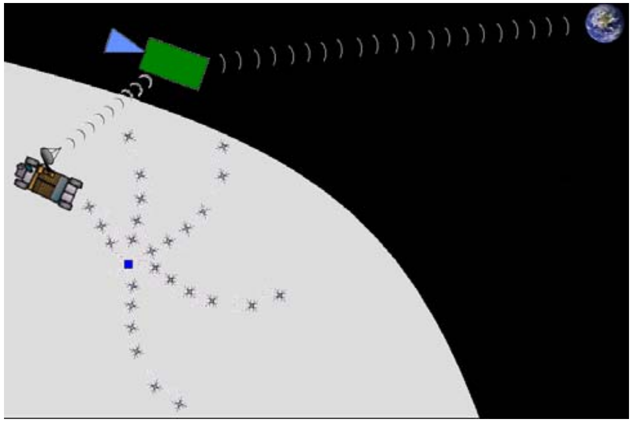
Total Cost – $1.631 Billion

LIRA Deployment

- **Scope: moving clusters and communication relays to desired positions**
- **Element Offloading**
  - Ramp and winch on lander
  - Elements packaged for simple attachment to offloading system
- **Additional Functionality of System**
  - Outfit lunar orbiting stage with simple radio communication system
  - Provide contact with Earth before laser system is operational
- **Deploy with long-range unpressurized rover**
  - High-capacity rechargeable batteries interface with array power system
  - Robotic manipulator (ramp) for loading and unloading of cargo
  - Interface with communication relays: gimbaled laser receiver
  - Radio antennas for communicating with telescope components and Earth during deployment
  - Range ~165 km, mass ~1000 kg, payload 480 kg
- **Opportunity for leveraging manned program: human-mediated deployment**
  - Astronauts can guide deployment rovers via laser link or short-range radio relay
  - Allows for monitoring by IVA crew

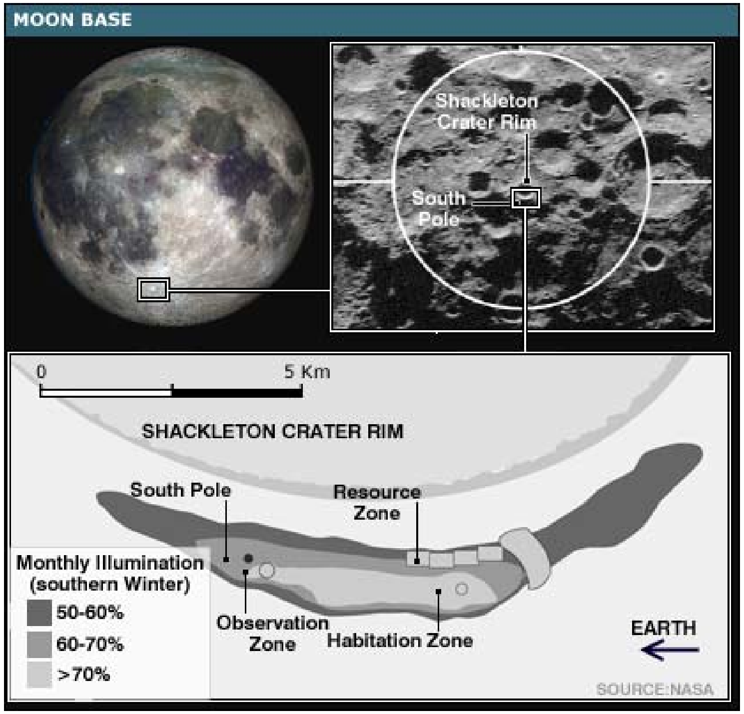


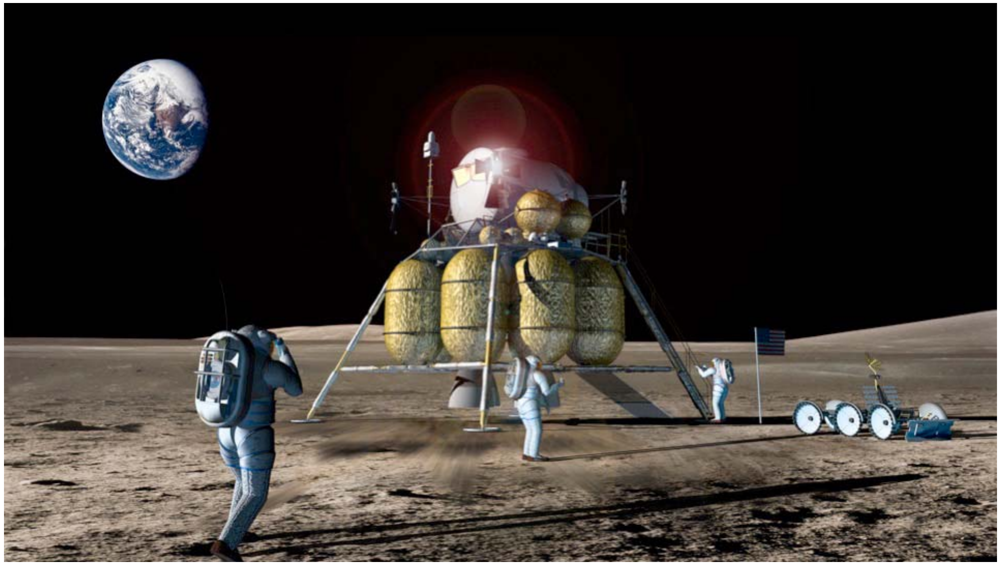




LIMIT Deployment

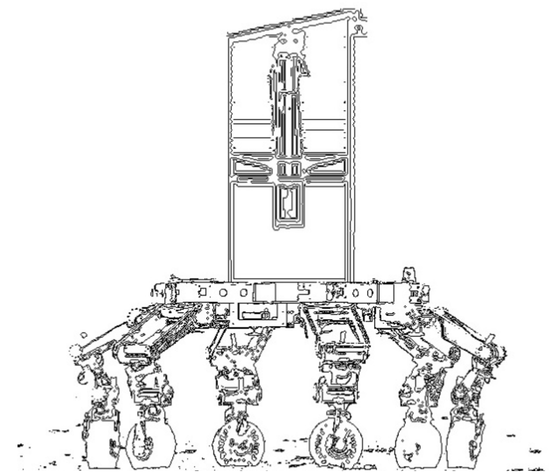
- **Human Lunar Outpost at South Pole**
- **Rovers (JPL's ATHLETE)**
  - Payload capacity of 450kg/vehicle
  - Move at 10km/h over Apollo-like terrain
  - Deployment will take 3 astronauts and 2 ATHLETES 2-3 weeks

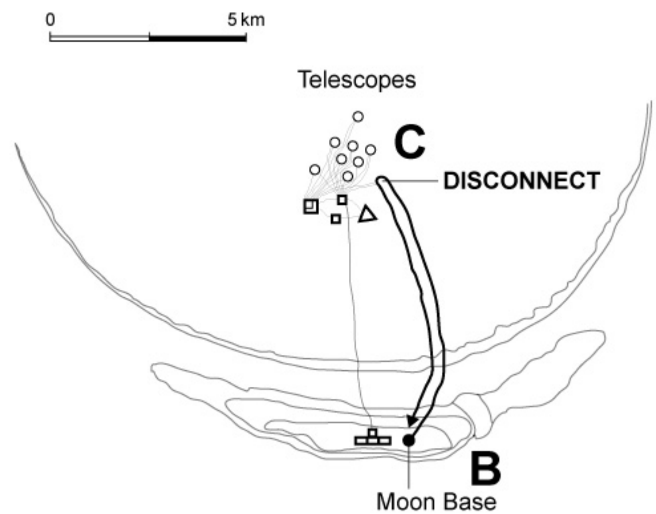




LIMIT Servicing

1. **Servicing Preparation**
   - Mirror covers close
2. **Retrieve Malfunctioning Component**
3. **Repair at Lunar Outpost**
4. **Reinstallation**
5. **Observation**
   - Dust settles down
   - Mirror covers open





Key Findings

- **Key Stakeholder value-delivery loop: Congress-NASA-Public/Media-Congress**
  - Flows are knowledge/images/photos, money, and political support
- **Lunar Interferometric Radio Array (LIRA)**
  - 62 km diameter baseline, low frequency radio telescope containing 3440 dipole antennas
  - Concept specifically enabled by radio quiet on far side of the Moon
- **Lunar Infrared Modular Interferometric Telescope (LIMIT)**
  - NIR/FIR Golay-9 array with 0.85 m elements, using operationally testing instruments and optics
  - Located in Shackleton Crater, allows for precise, stable baseline; serviceability; and modularity

Impacts

- **Requirement(s) impacted (pending RICWG review)**
  - *Include requirement number, any TBD / TBR numbers, text*
  - *Identify TBDs and TBRs recommended for closure or change (from / to language)*
  - *New requirements recommended*
- **Issue(s) impacted by analysis**
  - *Issue number and description of issue*
  - *Description of impact to issue (resolved?)*
  - *New issues identified – include description and resolution plan if possible*
- **Risk(s) impacted by analysis**
  - *Risk number and description*
  - *Description of impact or changes to risk (recommend closure?)*
  - *New risks identified to be entered into IRMA*
- **Impacts to SDR**
  - *A description of any impacts to the Cx SDR that are a result of the analysis*
- **Other impacts**
  - *A description of any impacts to Technical Data, Ops Concepts, etc. that involve other teams and may change their work or procedures*
- **Potential impacts to IDAC4, PDR, future work identified**
  - *Candidate analysis tasks identified to be performed by your or any organization in IDAC4 as an outcome from IDAC3 efforts*

Recommendations

- **Recommendations**
  - *Dedicate one full Ares V cargo launch (LIRA) or partial Ares V cargo or resupply launch (LIMIT) to deployment of a lunar telescope facility*
  - *Allow for possible EVA servicing/deployment, or IVA remote deployment by lunar habitat crews*
  - *Begin preparing public relations campaign to ready Hubble-type loop on stakeholder value-delivery network*

Thank You!

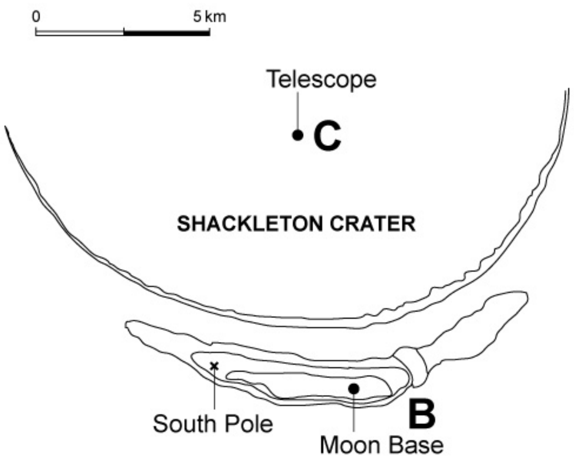
Backup

LIMIT System Components

- **System components to be launched from Earth**

	Quantity	Mass of each [kg]	Area [m^2]	Volume of each [m^3]	Location
Telescopes					
Telescope + Insulation + Base structure	9	138	-	2.00	C
Fiber optic cabling	1	7.6	-	0.25	C
Beam Combiner					
Beam combining unit	1	300	-	3.75	C
Thermal cryocooler	1	40	-	0.25	C
Power					
Solar panels	1	27	2.25	-	B
Batteries	1	354	-	0.0052	C
Support equipment	1	27	-	-	B
Power cabling	1	1184	-	1.00	B-C
Power distribution box	2	50	-	0.25	B,C
Electronics & Communication					
Computer	1	9.7	-	0.01	C
Radio transmitter	1	3.6	-	0.28	C

TOTAL SYSTEM (plus integration)		**4,400**			



Launch Cost Estimate

$$\frac{\text{Total system mass}}{\text{Ares V payload}} = \frac{4{,}400\text{ kg}}{18{,}000\text{ kg}} \approx 25\%$$

$$\text{Launch Cost} = 25\% \text{ of } \$1{,}260\text{M}$$

$$\approx \$308\text{M}$$

Deployment Time

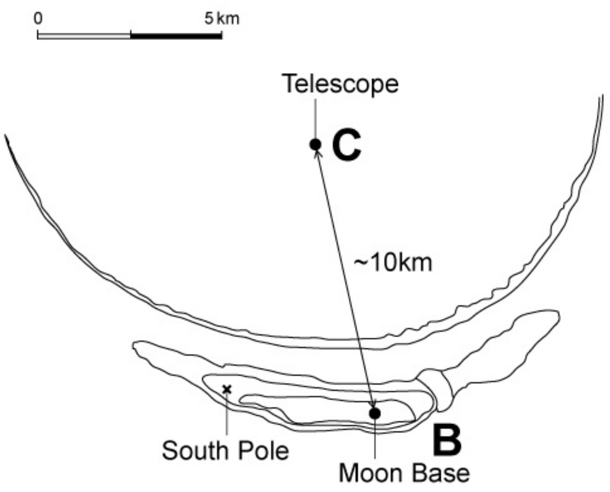
♦ Assumptions

- 3 astronauts and 2 ATHLETEs
- 6-8 hours of EVA at one time (day)

→ 4-6 hrs for operations + 2 hrs for round trip

ATHLETE: 10km/h

→ 2 hours for round trip



	Quantity	Operation Time of each [hrs]	Total Operation Time [hrs]	EVA # or Day [days]
Telescope	9	4	36	9
Fiber optic cabling	1	4	4	1
Beam combining unit	1	2	2	0.5
Thermal cryocooler	1	2	2	0.5
Solar panels	1	4	4	1
Batteries	1	4	4	1
Support equipment	1	2	2	0.5
Power cabling	1	4	4	1
Power distribution box	2	2	4	1
Computer	1	2	2	0.5
Radio transmitter	1	4	4	1
TOTAL EVA			68	17

Deployment Time Estimate

$$\frac{\text{Total operation time}}{\text{Operation time in one EVA}} \approx \frac{68\ \text{hrs}}{4\ \text{hrs}} = 17$$

Deployment will take approx. 2-3 weeks.

Thermal Control System Design

- **Cooling of collector units (IR mirrors)**
  - Passively cooled to 9 K with adequate shielding
- **Cooling of combiner units (IR detector)**
  - Actively cooled to 5 K with cryocooler
    - Several architectures under consideration
    - Target specifications
      - Performance: 20 mW capacity @ 6 K
      - Mass: 40 kg
      - Input power: 250 W
- **Heat rejection system**
  - Radiation panels and/or loop heat pipes

Advantages of lunar environment

  - Permanent darkness of crater interior on south pole
  - Little variation in temperatures
- **Requirements**
  - Highly sensitive IR detectors need cooling to < 5 K
  - Cold telescope/optics required to limit thermal emission
  - Target operating temperatures
    - IR mirrors (collector units): 9 K
    - IR detector (combiner unit): 5 K
- **External heat sources**
  - Cosmic microwave background
  - Geothermal heat flow
  - Reradiation from illuminated regions (crater rim)
- **Expected temperatures**
  - CMB: 4 K
  - Lunar blackbody radiation: 24 K
  - Crater surface with contributions from rim reradiation: 40 – 80 K

- **Compare longest wavelengths for other space IR telescopes to mirror temperatures**
  - Using Wien's Displacement Law,

$$\lambda_{\max} T_{BB} = 2898$$

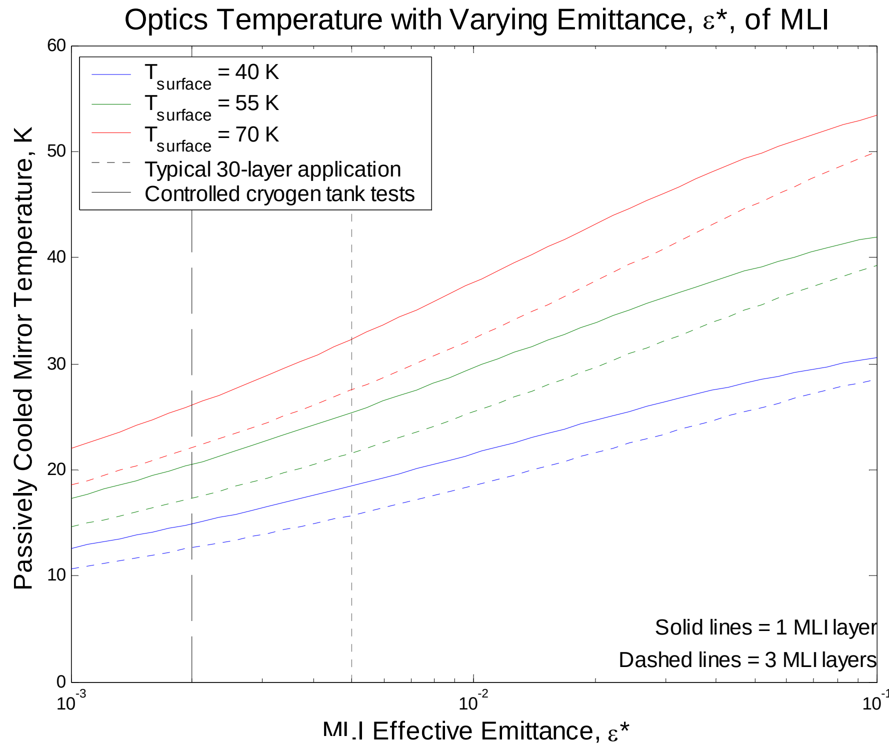
fit mirror temperature to curve based on farthest IR wavelength

$$\lambda_{\text{target}} T_{mirror} = \frac{\lambda_{\max} T_{BB}}{A} \longrightarrow A = 3.7$$

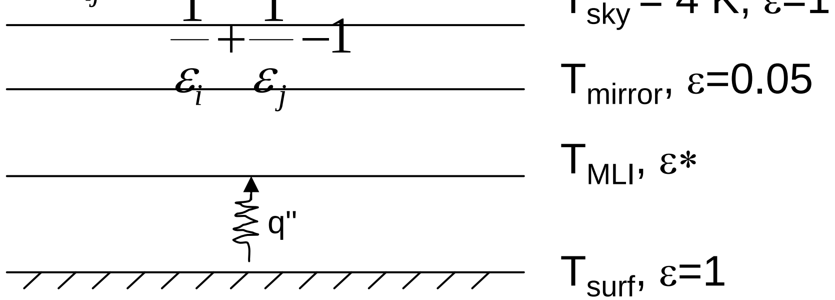
$$T_{mirror} = \frac{2898}{3.7\lambda_{\text{target}}}$$

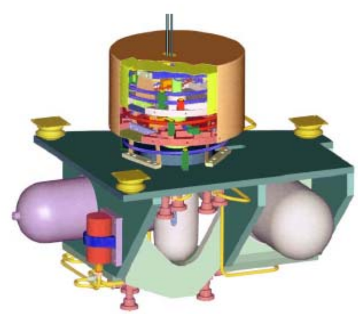
Passive Thermal Control of Individual IR Telescopes

- **Effects of Multilayer Insulation (MLI) effective emittance, ε *, on achievable temperatures**
  - Modeled as large re-radiating shields
  - Leverage cryocooler development from NASA's Advanced Cryocooler Technology Development Program (ACTDP)



$$q_{ij} = \frac{A\sigma\left(T_i^4 - T_j^4\right)}{\frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_j} - 1}$$





Beam Combining Device

ARGOS

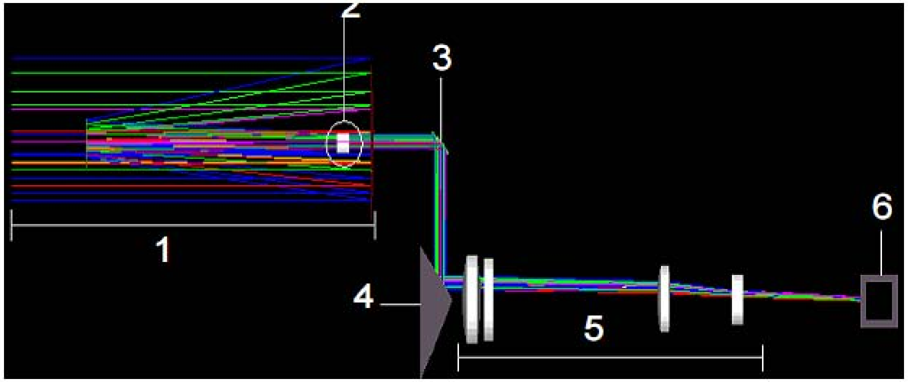
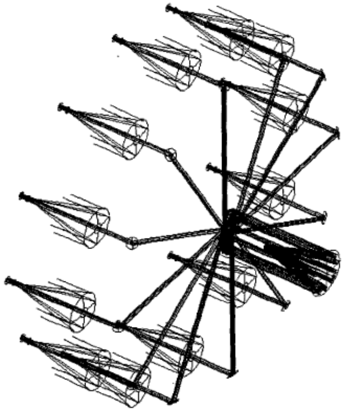
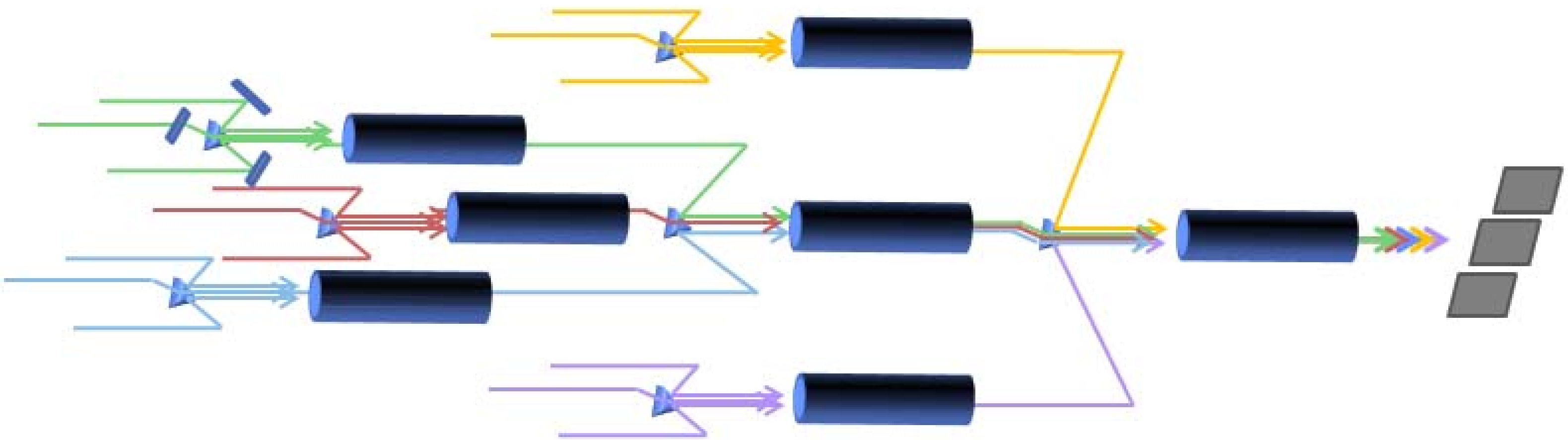


Figure 4.27 The final layout of the ARGOS optical train (only one aperture shown) 1-subaperture, 2- collimating lens, 3-FSM/ODL actuator, 4-pyramidal mirror, 5-beam combiner, 6-CCD

Single-stage



LIMIT Beam Combining Unit



Future Work

- **Further design trades and optimization studies**
  - RF: Noise attenuation, array configuration, laser relays
  - IR: Fiber optics, beam combining, thermal, dust, array configuration
- **Data collection on conditions on the lunar far side (via manned program or LRO)**
- **Develop a launch schedule that would fit into NASA's planned program**
- **Develop technology to deploy and operate LIRA telescope (deployment rover, laser communications)**

Concept Space Matrix

- Lunar Interferometric Radio Array (LIRA)
- Lunar Infrared Modular Interferometric Telescope (LIMIT)

JWST LIMIT LIRA

<table>
<tr><td>Collecting</td><td colspan="4">Monolithic</td><td colspan="7">Segmented</td><td colspan="8">Sparse</td></tr>
<tr><td>Pointing</td><td colspan="4">Reflecting</td><td colspan="7">Refracting</td><td colspan="8">Direct</td></tr>
<tr><td>Localizing</td><td colspan="4">Moving Primary</td><td colspan="7">Moving Secondary</td><td colspan="8">Static</td></tr>
<tr><td>Waveband</td><td colspan="2">Radio</td><td colspan="2">Radio/ Far IR</td><td colspan="2">Far IR</td><td colspan="3">Mid IR</td><td colspan="2">Near IR</td><td colspan="5">Near IR/Vis</td><td colspan="3">Visual</td></tr>
<tr><td>Location A</td><td colspan="4">Earth</td><td colspan="7">Moon</td><td colspan="8">Deep Space</td></tr>
<tr><td>Location B</td><td>Surface</td><td colspan="3">Orbit</td><td colspan="4">Surface</td><td colspan="3">Orbit</td><td colspan="4">EM</td><td colspan="4">ES</td></tr>
<tr><td>Location C</td><td>Place</td><td>Lo</td><td>Hi</td><td>G</td><td>Lo</td><td>Hi</td><td>Eq</td><td>P</td><td>Lo</td><td>Hi</td><td>Ecc</td><td>1</td><td>2</td><td>3</td><td>4/5</td><td>1</td><td>2</td><td>3</td><td>4/5</td></tr>
<tr><td>Location D</td><td colspan="4"></td><td>Nr</td><td colspan="2">Fr</td><td>L</td><td colspan="3"></td><td colspan="8"></td></tr>
</table>

Total Possible Concepts After Matrix Enumeration: 6048

Moon Dust Issues

- **Mechanical**
  - Dust varies in size and shape and can infiltrate and contaminate mechanisms
  - Dust is electrostatically charged and is hard to remove
- **Optical**
  - Scattering, diffraction
    - Dust on mirrors disrupt source signal from reaching detectors
  - Emission
    - Detector infiltration serious problem
    - Thermal issues of dust on optics → found not to be a problem

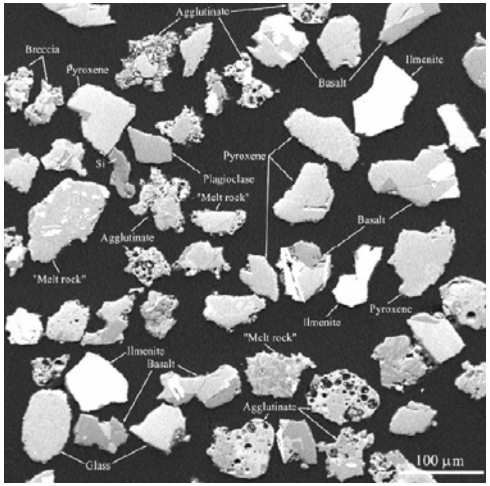
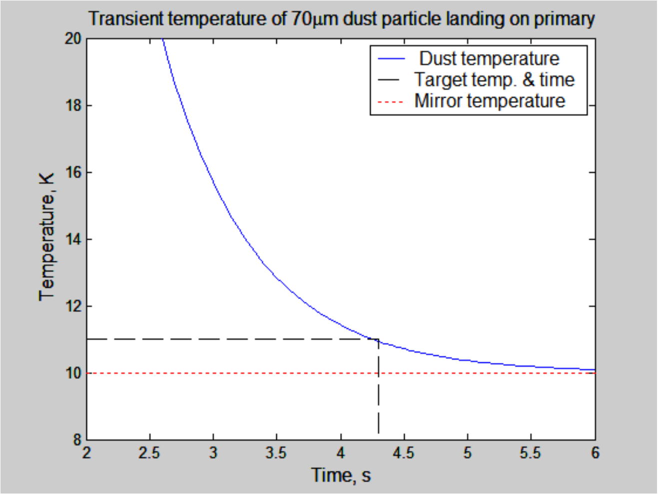


Photo courtesy of NASA



Dust Mitigation Concepts

- **Sealing/containment**
  - Sensitive instruments need tightly sealed designs and redundant layers of protection
  - Landing site built with containment wall to limit dust dispersion
- **Moving mechanisms**
  - Loose, flexible covers with well sealed interfaces, allowing rotation/movement while keeping dust out
- **Mirror covers**
  - Cover during launches/landings since kicked up dust is distributed over Moon's surface many tens of kms
- **Regolith sintering**
  - For serviceability by humans or robots, sinter lunar surface with microwaves reduces amount of lofted dust
  - "Glass road"
- **Electrostatic cleaning based on sequence of ac pulses**
  - Testing conducted by Carlos I. Calle (lead scientist at NASA's Electrostatics and Surface Physics Laboratory at Kennedy Space Center) worked well
  - Looking to obtain real Moon samples
- **Polyimide mirror coating to reduce sticking**
  - Low surface energy reduces attraction
  - Harder, more resistant than Teflon
- **Ultrasonic vibration to move dust off optics**
  - Zenith-pointing through Cassegrain
  - Horizon-pointing off edge of mirror

Image of HTP flexible seal, removed due to copyright restrictions

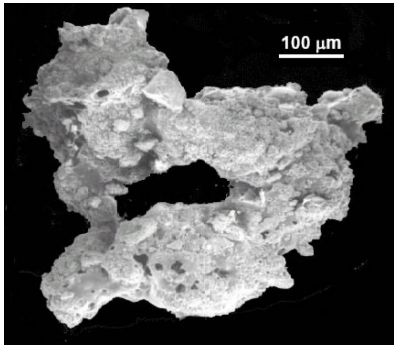


Image of vehicle chassis, removed due to copyright restrictions

Moon Dust Photos courtesy of NASA

Electronics

- LIRA Requirements
  - 14 Gbps Input
  - 839 Mbps Output
- Design Results
  - 46 Data Input Cards Required
  - 6 Equipment Enclosures
  - Total Weight: 58.2 kg

Image of Single Equipment Enclosure, removed due to copyright restrictions

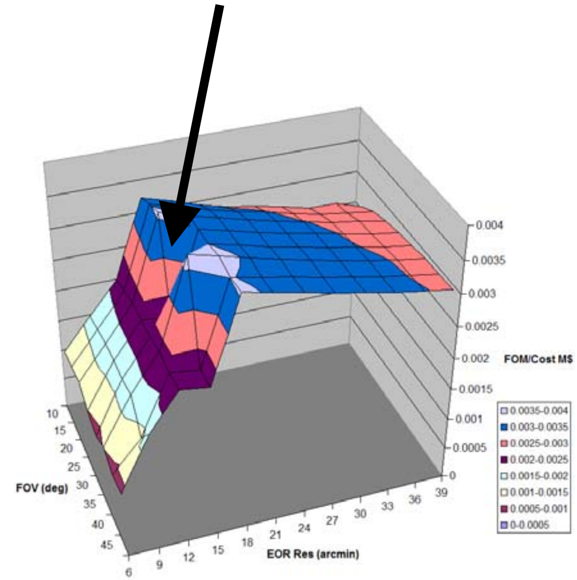
- LIMIT Requirements
  - 1 Gbps input
  - 500 Kbps output
- Design results
  - 8 data input cards required
  - 1 equipment enclosure
  - Total weight: 9.7 kg
  - Chips throughput: 1.575Gbps

- Assumptions
  - Equipment Properties from Broad Reach Engineering Website
  - $4.7M per Enclosure
- Relationships
  - Input increases with number of antennas, clusters and cluster data rate
  - Output data rate increases with size of image and number of frequencies

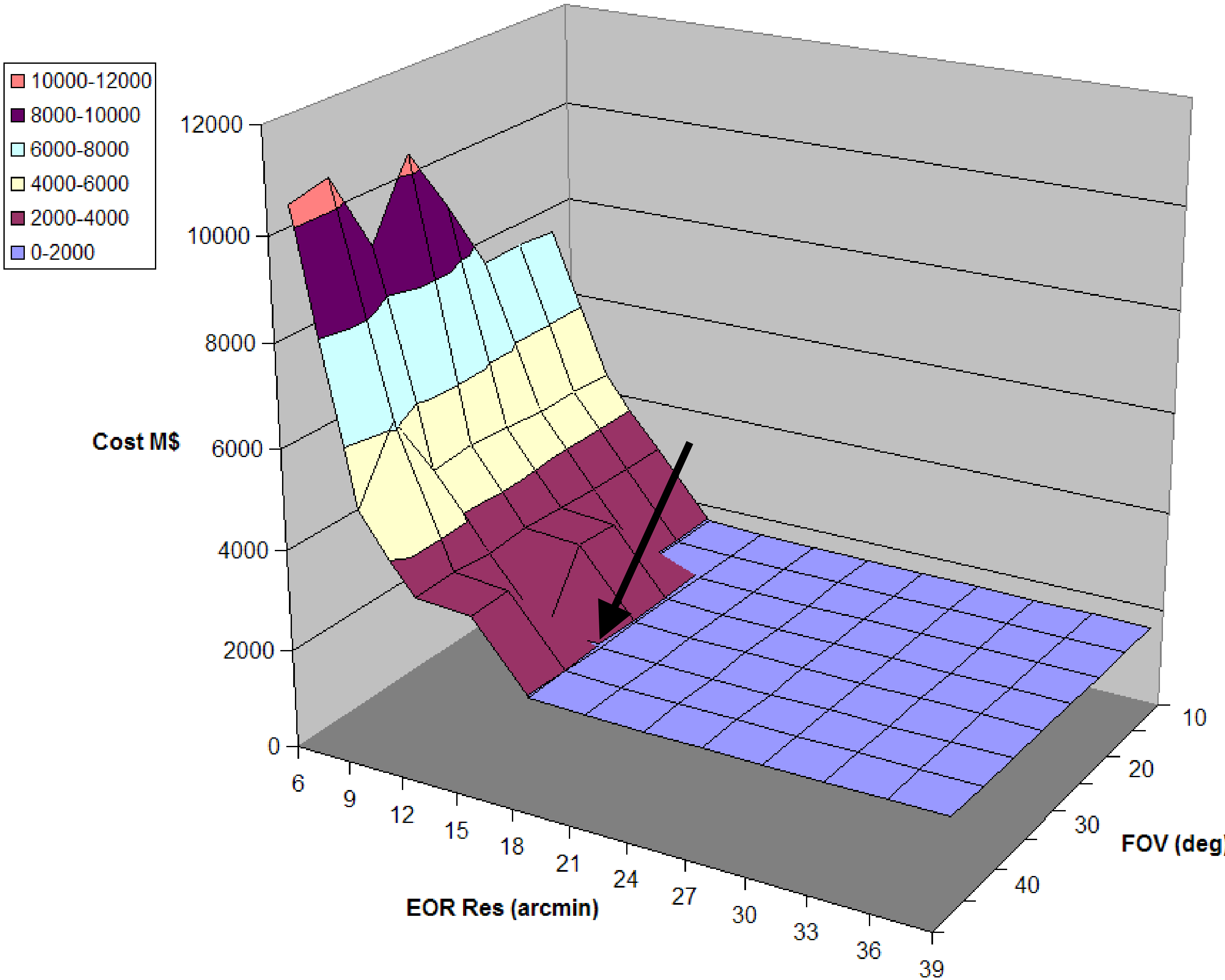
Science per Cost

- Developed a figure of merit combining a "discovery efficiency" metric with angular resolution
- t_{survey} represents the time it takes for a survey of half of the sky to a target sensitivity over the entire frequency band
- θ_{EOR} represents the resolution at which the EOR can be observed
- Logarithm and square root used to balance the components and reflect the fact that incremental increases in the capability become less important as the instrument becomes more capable

$$FOM = \text{Constant} \times Log\left(\frac{1/t_{survey}}{\sqrt{\theta_{EOR}}}\right)$$

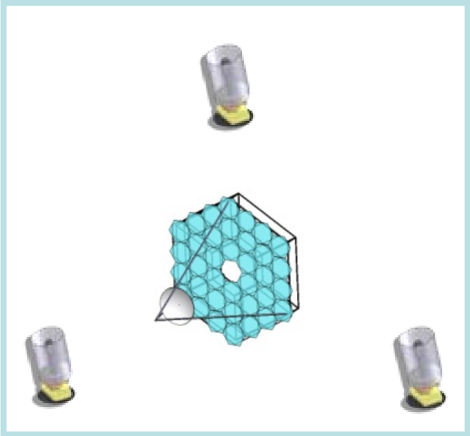


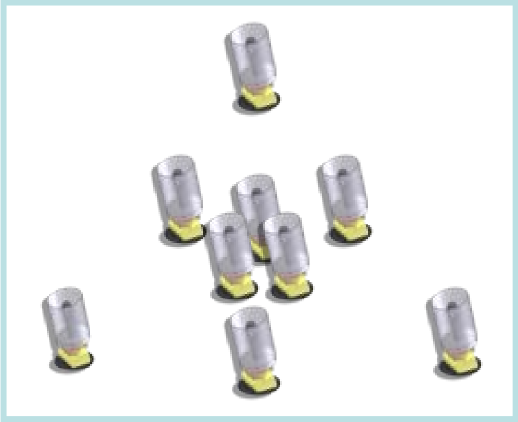
Cost vs EOR Resolution



IR Telescope Evolution

- **Architectures presented at previous review**
  - NIR/FIR interferometer with 1 m and 3 m elements
  - FIR segmented 14m telescope
- **Hybrid architecture considered after review**
  - Central Fizeau array with long baseline outriggers
  - Cost of hybrid design would almost double
  - Observing time split between imaging and interferometry
- **Final concept selected**
  - NIR/FIR Golay-9 Fizeau array with 0.85 m elements





Array Design Methodology (cont)

- Assume an instrument noise temperature of 100K and calculate the sky temperature as:

$$T_{Sky} \cong 100\left(\frac{\nu}{200\mathrm{MHz}}\right)^{-2.8}$$

- Assume a 4σ detection level in 2000 hours and solve for N
- Determine FOV by size of cluster and max resolution by size of array as:

- Where D is the cluster size and array size respectively

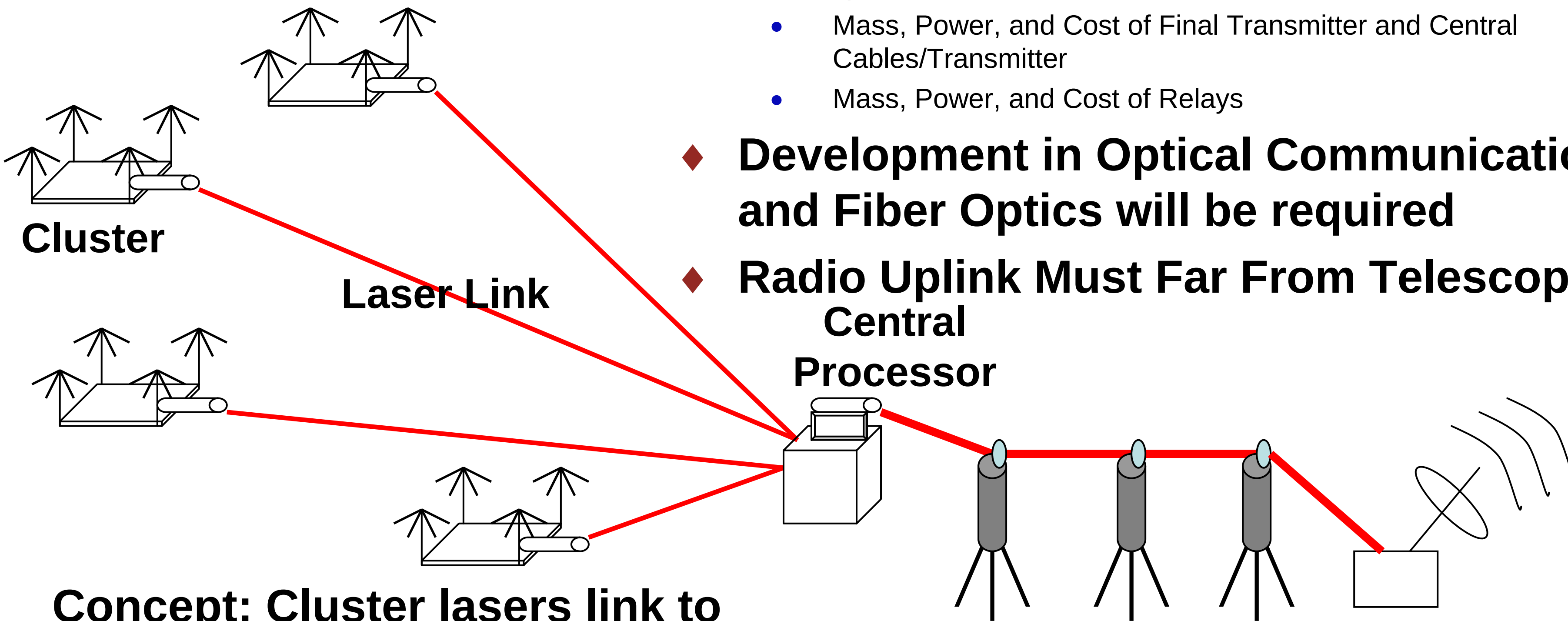
$$\theta \sim \frac{\lambda}{D}$$

RF Power Systems and Structures

- **Each Cluster**
  - 12-W solar-panel & batteries systems
  - Continuous operation with 70% sunlight
  - 19 kg & $7,000 power system
- **Central Processing Unit**
  - 230-W solar-panel & batteries systems
  - Continuous operation with 70% sunlight
  - 400 kg & $145,000 power system
- **Major Considerations**
  - Substituting RTG reduces mass by 380 kg but increases total cost including launch by $13M
  - Significant batteries required (4.2 ton) for 210-hr night
  - Locating telescope closer to equator significantly increases battery mass for a solar powered system and tends toward using an RTG for the central unit
- **Dipoles deploy From 1.6 x 1.6 meter square palette**
- **Final Size: 4.8 x 4.8 meters**
- **Footprint levels dipoles on lunar surface**
- **Requirements**
  - 215 clusters
  - 16 dipoles per cluster
  - 0.75 m dipole length
  - 62 km array diameter
  - 24 square meter cluster
- **Design Results**
  - $330,000 per cluster (not including power and communication)
  - 33 kg per cluster
- **Assumptions**
  - 0.1 kg/m dipole mass
  - 1 kg/m^2 structure mass
  - $10,000 per kg

Communication System - Radio

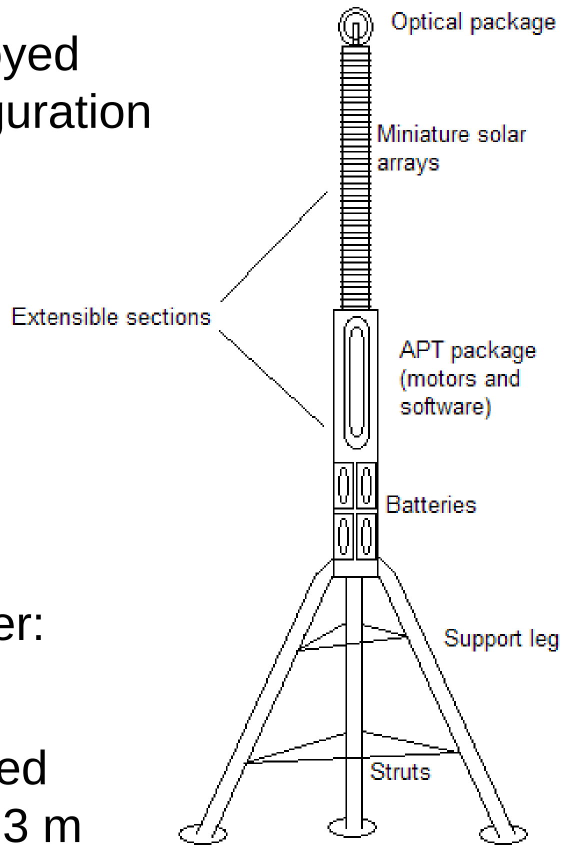
- **Design Inputs**
  - Number of Clusters
  - Distance to Nearest Transmitter Site
  - Data Rates
- **Design Outputs**
  - Mass, Power, and Cost of Final Transmitter and Central Cables/Transmitter
  - Mass, Power, and Cost of Relays
- **Development in Optical Communication and Fiber Optics will be required**
- **Radio Uplink Must Far From Telescope**



Concept: Cluster lasers link to central station; central station signal follows relay chain to downlink transmitter

Relay Concept - Radio

Deployed configuration



Max diameter: 0.15 m

Deployed height: 3 m

Estimated mass: 27 kg

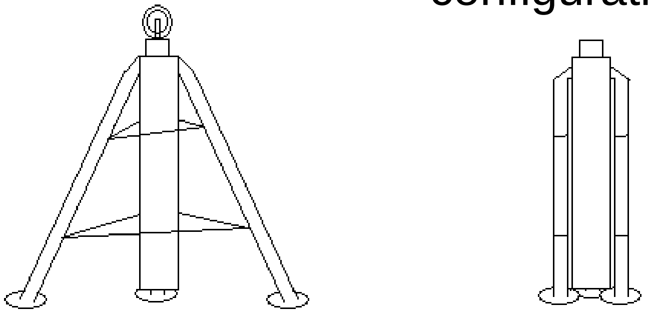
Estimated power: 0.5 W

Estimated cost: $27,750 each

Relay spacing: ~6 km

Partially deployed

Transportable configuration



- **Chain of Robust, Cheap Relays Link Telescope and Moon to Earth Transmitter (Set Risk, Try for Cost, Accept Time)**

Strengths of Stakeholder Value Loops

Value Loops	Science Objectives					
(Expected strength of each loop – "% strength")	A	B	C	D	E	F
Public → Congress → NASA → Scientists → Public	15	*11*	22	*14*	*13*	*3*
Public → Congress → NASA → Scientists → Media → Public	*7*	*7*	18	*11*	*13*	*2*
NASA → Contractors → Public → NASA	28	**37**	**56**	**44**	**43**	15
NASA → International Partners → Scientists → NASA	**47**	28	**38**	28	33	15
NASA → Scientists → Public → NASA	19	15	**35**	22	22	*5*
Congress/Executive → NASA → Telescope Operator → Scientists → Public → NASA	15	*11*	22	*14*	*13*	*3*
AVERAGE	22	18	32	22	23	7
NORMALIZED AVERAGE	**0.68**	**0.58**	**1.00**	**0.70**	**0.71**	**0.22**

A. Epoch of Reionization (EoR)
B. Active Galactic Nuclei (AGN)
C. Extrasolar Planets (XSP)
D. Galaxy and Star Formation (GSF)
E. Dark Energy (DE)
F. Weak Gravitational Lensing (WGL)

Averaged and Normalized Utility Scores

Stakeholder Utility	Science Objective					
(0 = no utility; 1 = maximum utility)	A	B	C	D	E	F
Congress & Executive	0.78	0.77	0.62	0.61	0.59	0.53
NASA	0.70	0.70	0.60	0.55	0.65	0.45
Scientists	0.75	0.80	0.45	0.42	0.50	0.45
Media	0.47	0.60	0.80	0.80	1.0	0.60
Educators	0.50	0.70	1.0	1.0	0.75	0.40
General Public	0.40	0.53	0.93	0.80	0.67	0.33
International Partners	1.0	1.0	1.0	1.0	1.0	1.0
Contractors	1.0	1.0	1.0	1.0	1.0	1.0
Telescope Operator	1.0	1.0	1.0	1.0	1.0	1.0

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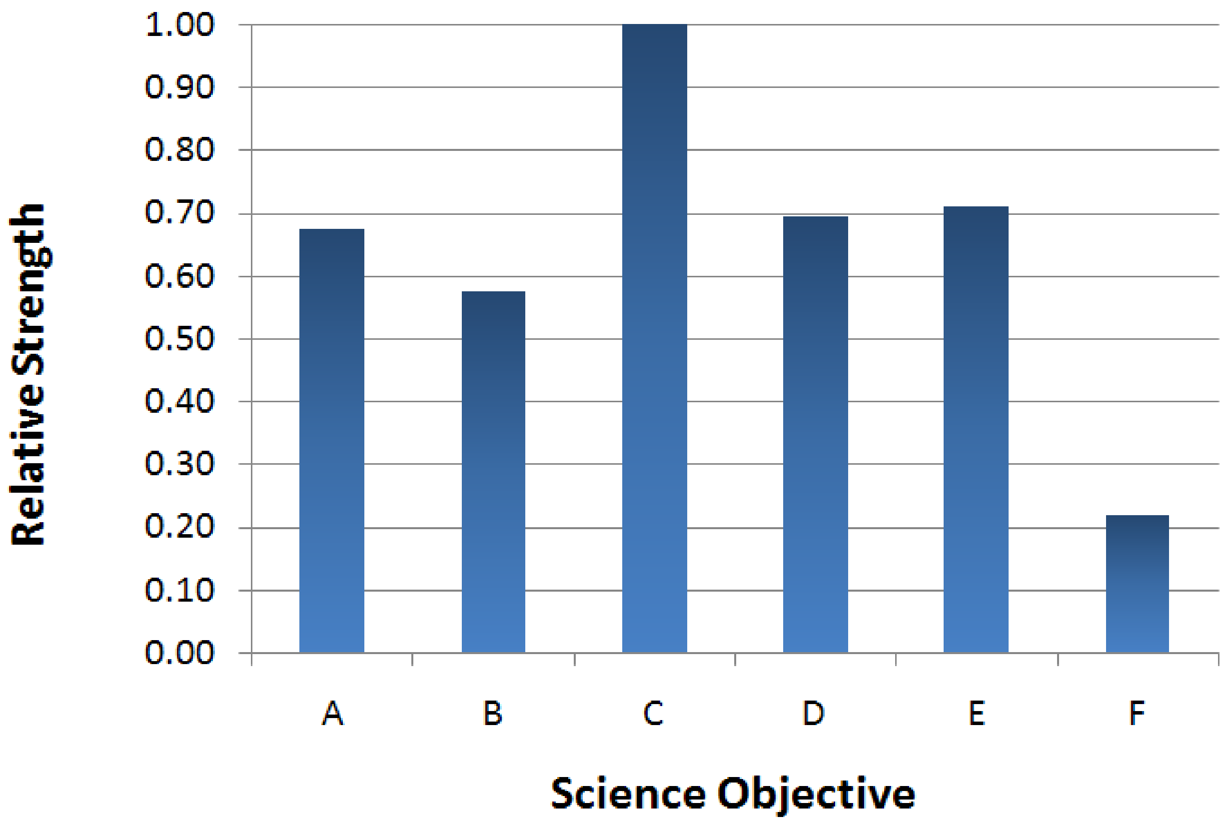
Ranking of Science Objectives



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Communication Relays

- **Chain of Robust, Cheap Relays Link Telescope and Moon to Earth Transmitter (Set Risk, Try for Cost, Accept Time)**

Transmit to Earth from Lunar limb

From 85° latitude

24 laser relays