Robotic Missions in Support of Human Lunar Operations

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Human/Robotic Operations on the Moon will be Integrated and Synergistic

- Lunar Science Exploration Goals
  - Met through reconnaissance orbiters and landers, robotic assistants
  - Support human exploration
- Human exploration
  - Base site preparation—enable landing after safe havens established
  - Re-supply—enable long duration exploration
- ISRU
  - Orbital reconnaissance, ground truth landers, demonstrations and pilot plants
  - Required to establish a functioning lunar economy, enable robust science, pave the way for commercial operations, perhaps NASA's exit strategy for the moon
- Preparation for Mars
  - Robotics in developing technology and operations for Mars exploration

Synergy of Lunar Science and Exploration

- W. David Carrier III, soil scientist, asked the A-11 crew to photograph their bootprints on the moon
  - Soil mechanical properties
  - Porosity, cohesiveness
  - Trafficability

- This photograph is now one of the most famous in history
  - One of the iconic images of the Space Age
  - Demonstrates that we were there
  - Emblematic of what humans beings can achieve
  - Today, the science utility and rationale for this image is largely forgotten

Robotic Missions Prior to Human Landings

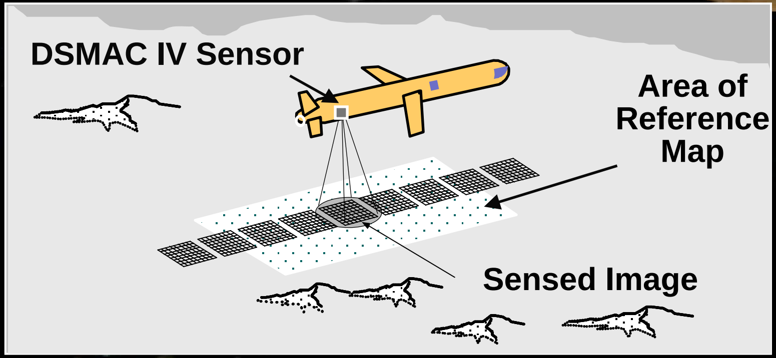
- Reconnaissance
  - Global high-resolution, multi-spectral maps of the moon
    - SCIENCE: Topography, illumination, mineralogy mapping….
    - EXPLORATION: Landing site selection
    - ISRU: Resource identification
  - Site surveys
    - SCIENCE: Regolith properties, three-D structure, gas and volatiles abundance
    - EXPLORATION: Landing site validation, detailed mapping, infrastructure emplacement
    - ISRU: Resource confirmation, extraction demonstration, pilot plant

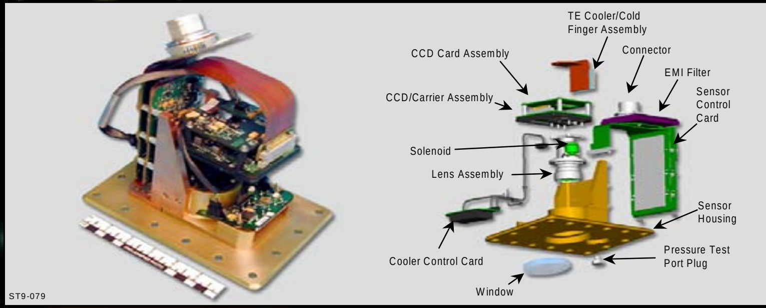
- Technology development needed
  - Capabilities:
    - Pinpoint landing—allows multiple visits to the same site
    - Autonomous systems—increases asset capability
    - ISRU systems—enables robust exploration and transition to commercial operations
  - Enabled by
    - Netcentric operations—link the assets for optimal performance
    - Telerobotic operations—reduce crew radiation risk, prepare for Mars

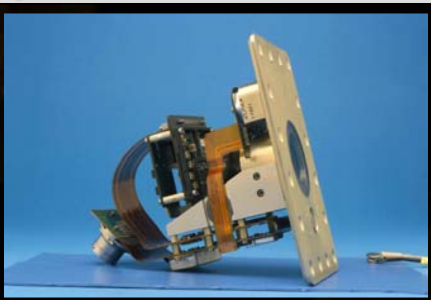
Science Enables Preparation for Human Lunar Exploration

Digital Scene Matching Area Correlator (DSMAC)

- Highly Accurate Navigation Aide since 1970s – Pre GPS
- Sensor
  - Optical device captures digital grayscale images
  - Images correlated against specified reference map images
- Flashlamp Illuminator
  - Provides lighting for use during night flights.

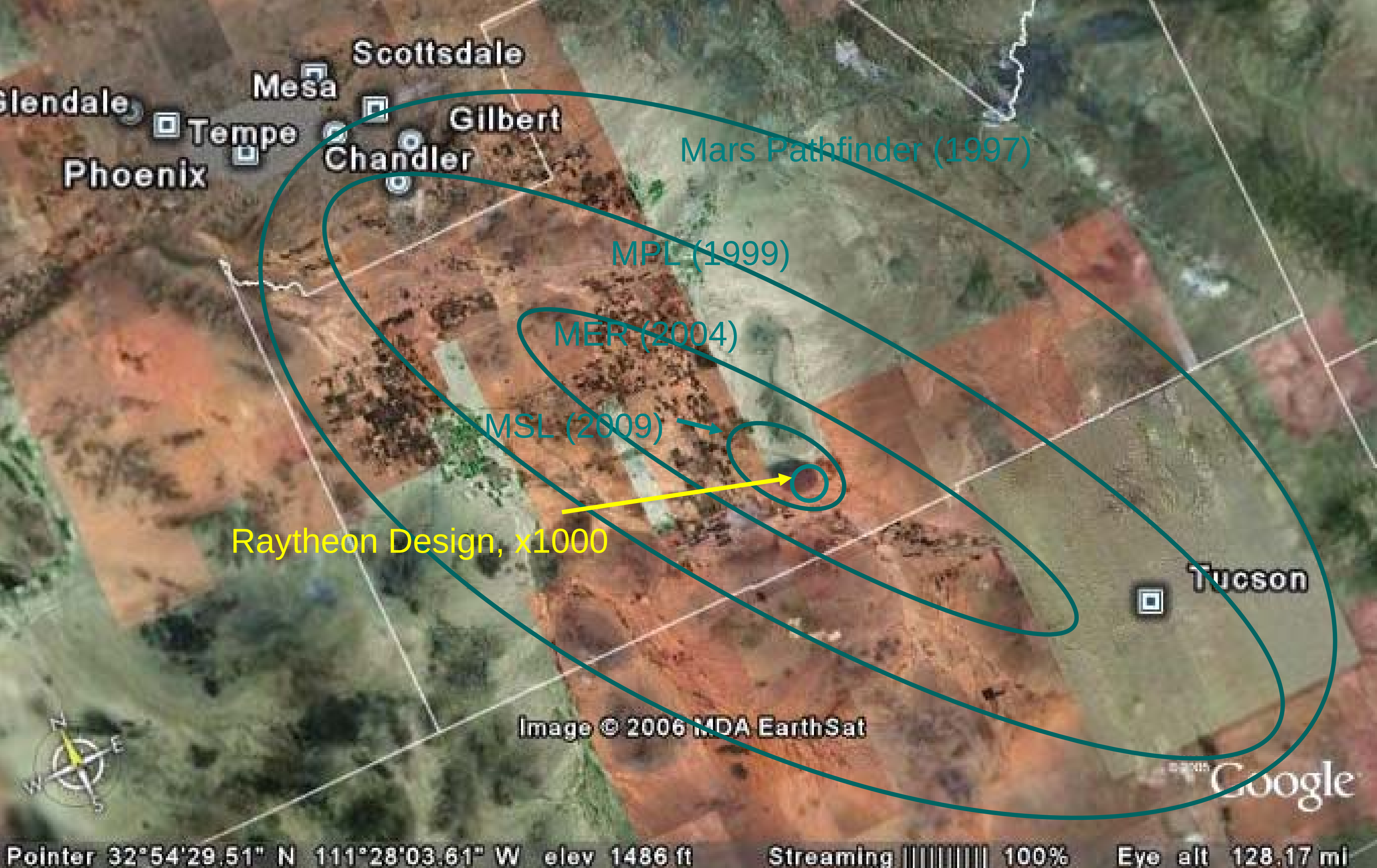






DSMAC is Accurate, Light, Affordable, Reliable and Readily Adaptable to Lunar Navigation Applications

Southeast Arizona Regional Map for Landing Precision Characterization Mission to Picacho Peak



Current Technology Limits Targeting of High-Value Science Sites

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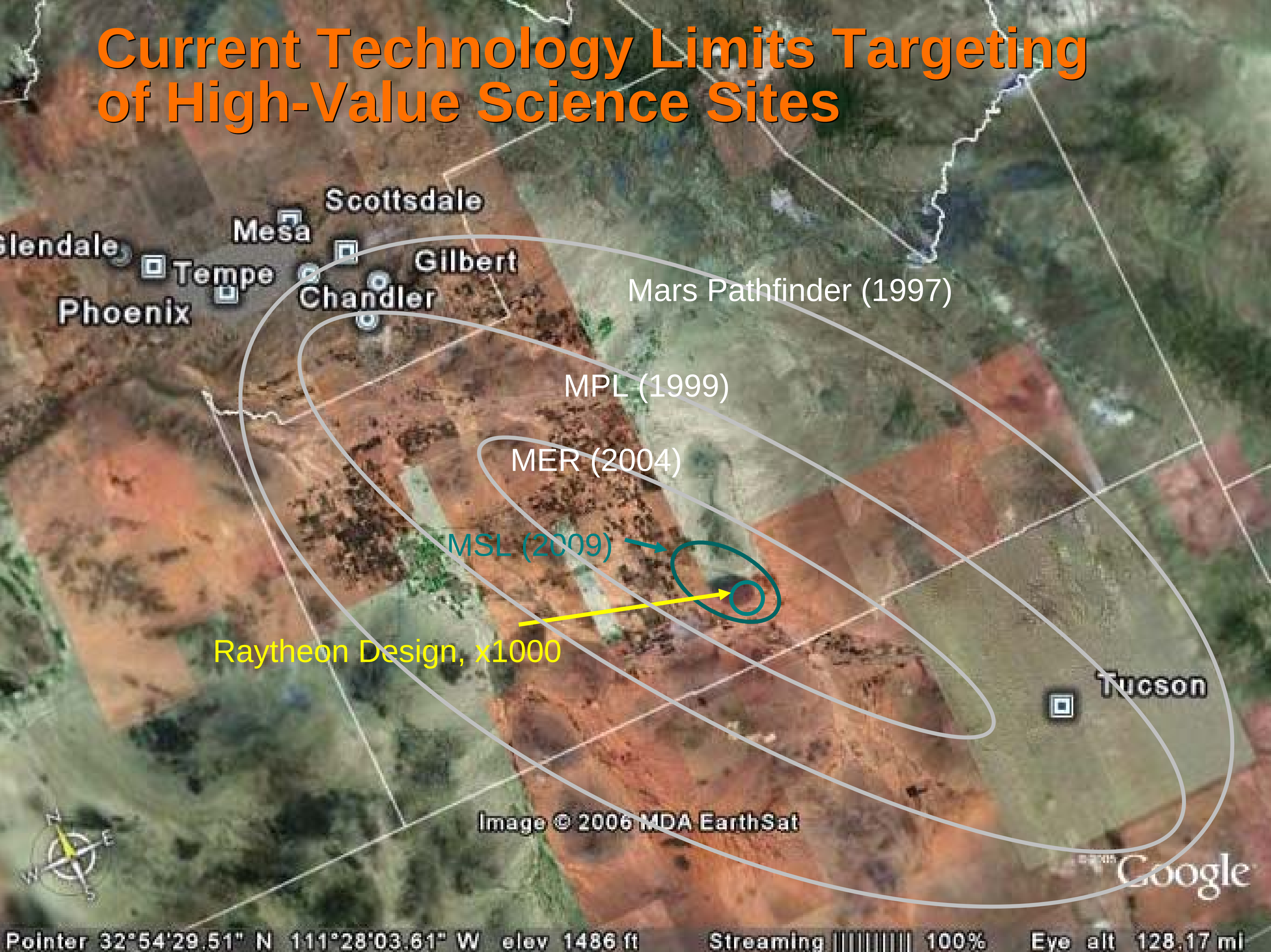

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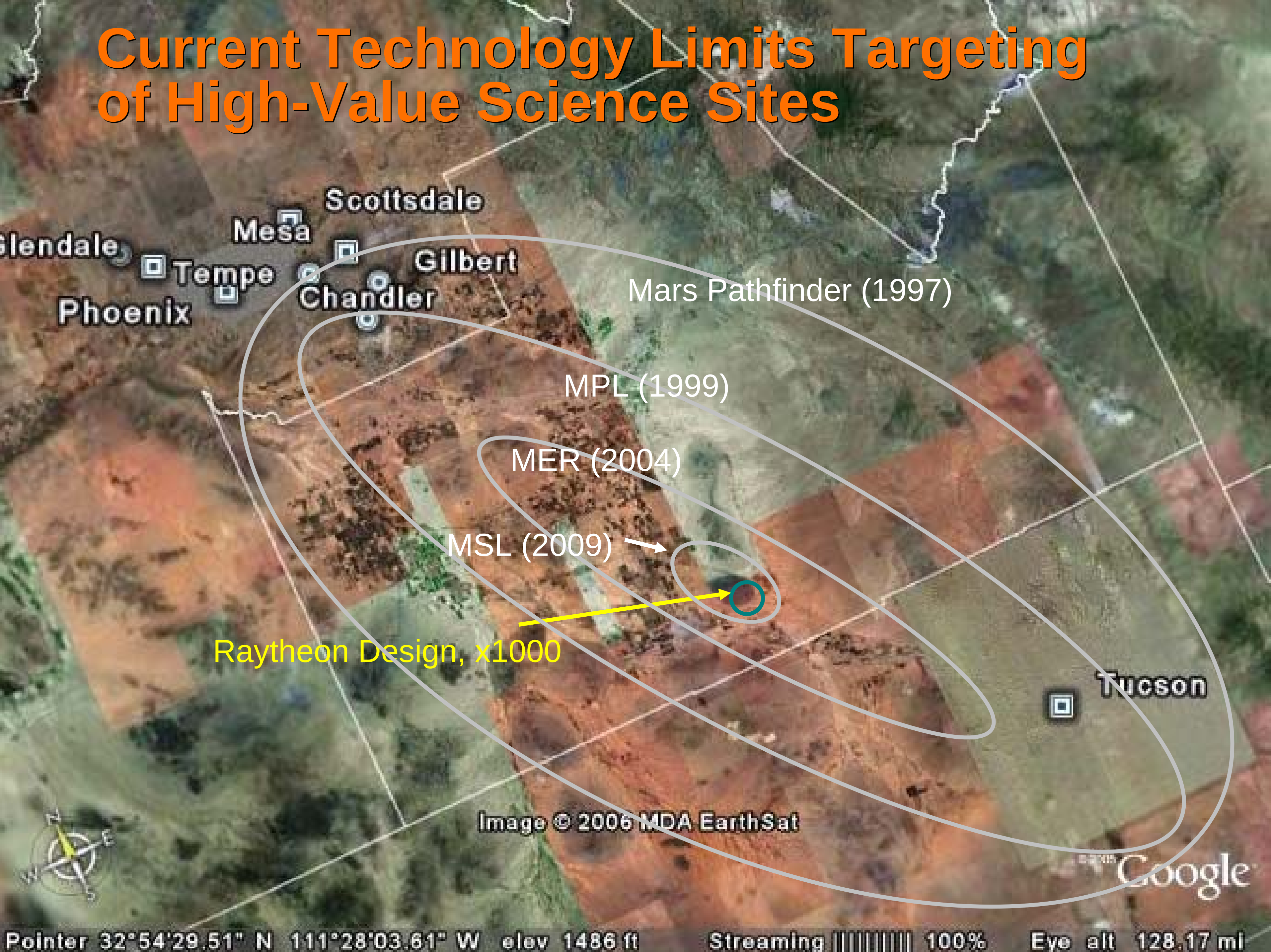
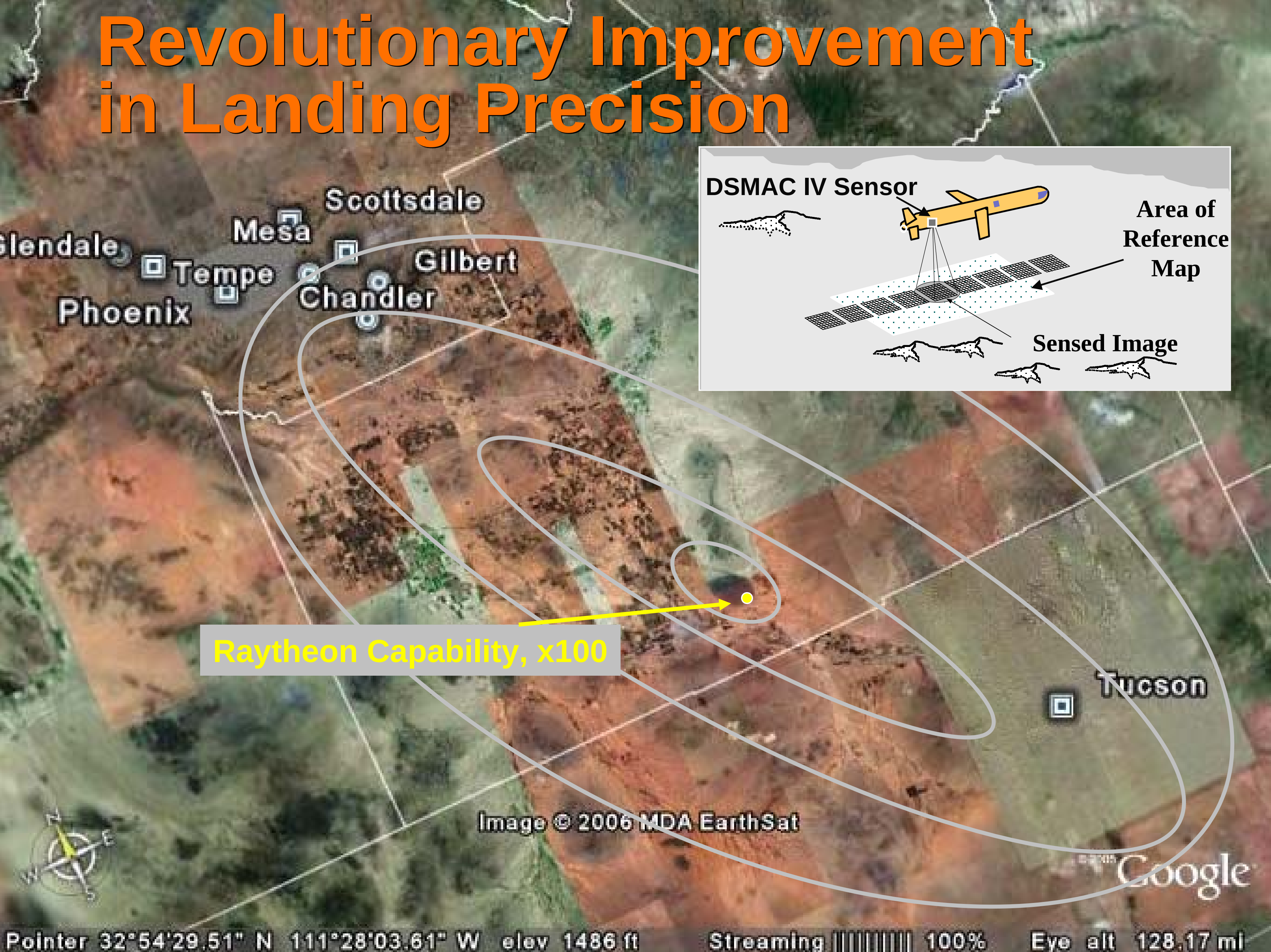


Revolutionary Improvement in Landing Precision



Lunar Robotic Precursors Blaze the Trail

	Reconnaissance	Establish Base	Human Exploration
Lunar Exploration Science Missions	LRO, Ice Finder, Ice Mapper (Recon); Site Survey; Solar Sentry; L-2 Relay	Robotic Precursors to Human Base Site (*)	Human Support . . .
Lunar ISRU Missions	Regolith Handling Demonstrators; Technology Precursors (LUNOX and Polar Volatiles)	Processed ISRU Demonstrator**	ISRU Pilots, Production†
Other Related Missions	ESA, India, China (International Missions)	Potential NEOs ISRU Precursors	

*Habitats, shielding, power, supplies, not in ESAS

** Choice of technology depends on earlier missions

† Provides air, water, propellants

Legend:
- ▲ (red) Human
- △ (blue) Robotics

Comprehensive robotic precursor program is essential for human exploration

Implementing the Vision

Non-ISRU Lunar Robotic Precursor System

Flight	Mass (kg)	Power (W)	Flight	Mass (kg)	Power (W)	Flight	Mass (kg)	Power (W)
Reconnaissance			*Base Site Preparation*			*Exploration*		
LRO	*~100*	*~200*	Preposition Power	2500	4000	Fuel Delivery	2400	TBD
Ice Finder	3 x 10	3 x 10	Preposition Cargo	2500	100	Hopper Explorer	100	100
Ice Mapper	2 x 250	2 x 120 (RTG)	Preposition Habitat	2500	1000	Short Range Rover	250	1000
Pathfinder	150	100				Long Range Rover	TBD	TBD
L2 Relay	*100*	*300*				*Solar Sentry*	*3 x 200*	*3 x 500*

13 landers, 7 with payload <250 kg (medium lift). 11 require pinpoint landing capability

Lunar ISRU Mission List

Flight	Mass (kg)	Power (W)	Precision (m)	Flight	Mass (kg)	Power (W)	Precision (m)
Regolith Moving Demo	150	500	100	Water Demo	100	300	10
Regolith Sintering Demo	150	500	100	LUNOX Pilot Plant	250	4000	100
Site Preparation	200	2000	10	Water Pilot Plant	225	2700	10
Habitat Shielding	3 x 500	3 x 7000	10	Cryo Mission	200	1000	10
LUNOX Demo	20	1000	100	Production Plant	2300 - 3400	60000	100

ISRU mass and power estimates based on Colorado School of Mines lunar factory models

12 landers, 8 with payload <250 kg. All require pinpoint landing

Candidate Robotic Missions for ISRU

- Expedite regolith handling, paving demonstration
  - Wide applicability
  - Conduct basic soil science
- Expedite regolith processing testbed on lunar surface
  - E.g., 3 demo package on lunar lander in 2010
- Pursue LUNOX and lunar ice simultaneously
  - Flexibility in base site selection
  - Prove out different technologies for Mars
- Sub-optimal solutions are OK

ISRU Cost & Schedule Savings Mandates Demonstration of Operations

Robotic Precursor System

- Notable Robotic Characteristics
  - 60% of precursors (15) require medium lift (small to medium lander)
  - Precision landing: ≤100 m required on nearly all landed flights
  - Teleoperational: Required on all rovers
- Recommend rapid development of new technologies
  - Precision landing
  - Autonomous systems
  - ISRU
- Recommend development of the lunar robotic lander as a commodity
  - Reduce or eliminate NREs through flexible, modular design
  - Non-optimal design, yet capable of delivering variety of payloads
  - Production run allows cost savings to be identified and realized

Required Tech Development will Benefit from Leveraging Existing DOD Systems

The Human Adventure is Just Beginning