PERFORMANCE ANALYSIS AND COMPARISON OF CLUSTERED AND LINEARLY DISPERSED OPTICAL DEEP SPACE NETWORK

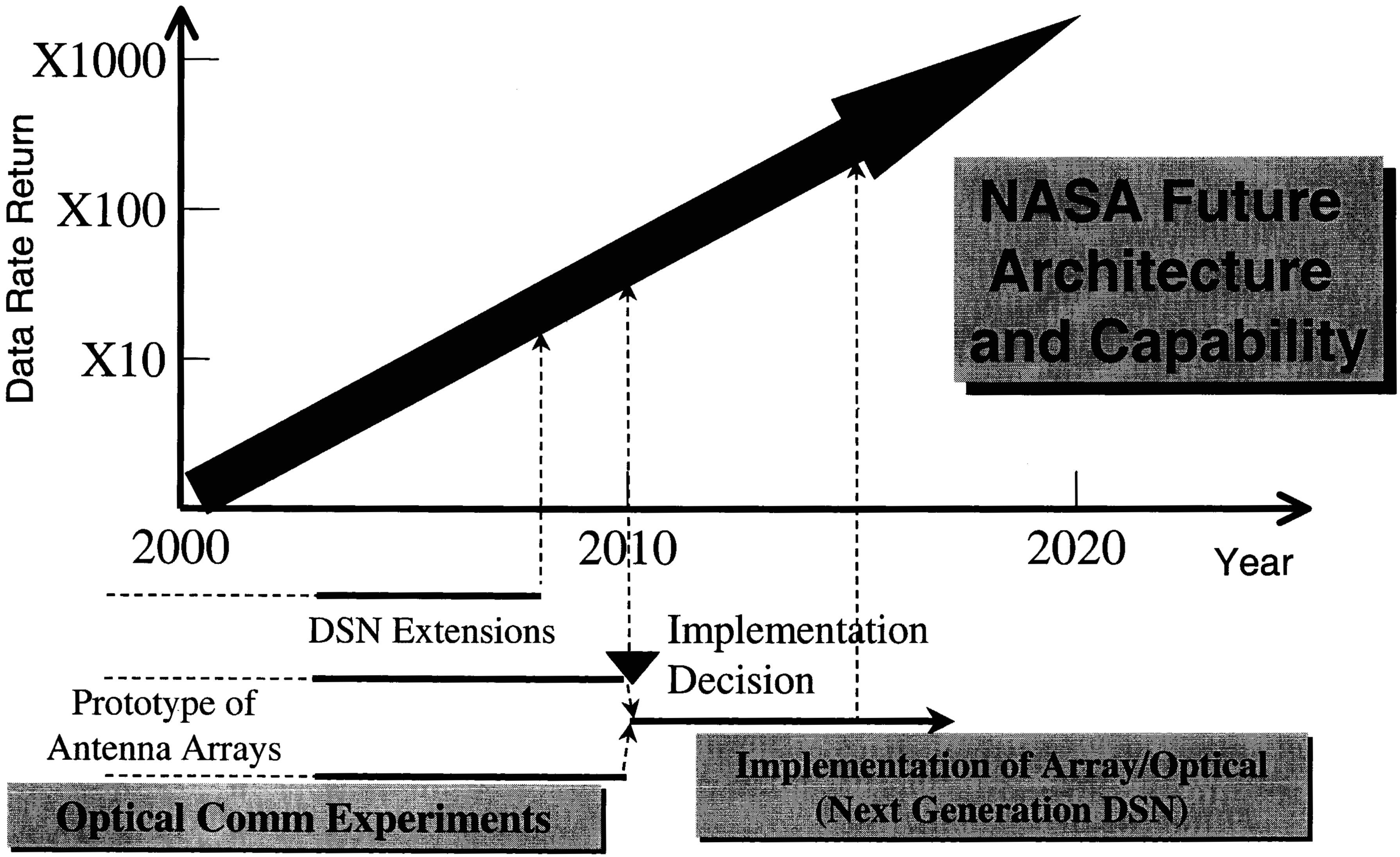
FARID AMOOZEGAR, ROBERT CESARONE, SABINO PIAZZOLLA (USC-IMSC), LESLIE PAAL, AND RICHARD EMERSON

5TH INTERNATIONAL SYMPOSIUM ON RCSGO
PASADENA, JULY 10 2003

OUTLINE

- Motivations
- Background
  - Linearly Dispersed Optical Subnet (LDOS) vs. Clustered Optical Subnet (COS)
- Technology Trends
  - Technological Advances
  - High Level Requirements
  - Optical Deep Space Network (ODSN) Mission Needs
  - New Architectural Solutions
- Cost Estimating Methods for ODSN
- Summary and Conclusion

Motivation



Data Rate Return
X1000
X100
X10
2000
2010
2020
Year
NASA Future Architecture and Capability
DSN Extensions
Implementation Decision
Prototype of Antenna Arrays
Optical Comm Experiments
Implementation of Array/Optical (Next Generation DSN)

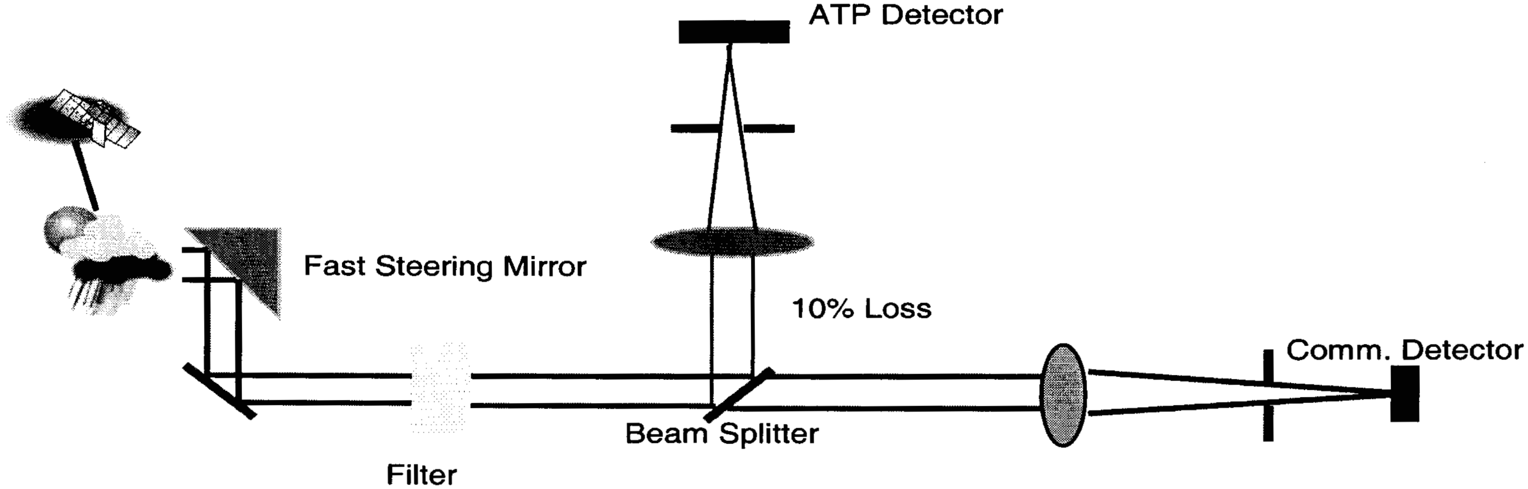
Deep Space Optical Communications

- Higher Data Return Rate
  - Up to 100 Mb/s for Mars TELESAT 2009
- Reduction of Mass and Power Consumption on S/C
  - Solar power drops below 100W/m^2 beyond 4 AU
  - RF falls short beyond 3 AU for high data rates
- Ground Receivers (Telescope) Performances Greatly Dependent on the Atmospheric Channel
  - Atmospheric Transmission
  - Background Sky Radiance
  - Cloud Coverage
- Need of Accurate Acquisition Tracking and Pointing (ATP)
- Need to find well behaved peaks (distance, altitude, clouds)

GROUND BASED ADVANCED TECHNOLOGY STUDY (GBATS-1994)

- First study on ODSN: **GBATS**
  - Global coverage of the Earth with high weather availability (90%)
  - Telemetry Reception: Night-time and Daytime (up to 10^0 of SEP)
  - Acquisition of the signal within 20 minutes at 15^0 of elevation
  - Fine Pointing Mechanism with 0.01 mrad of accuracy
  - A Number of 10m Aperture Telescopes in Distributed in Space Diversity to mitigate the weather effects
  - Baseline performance – equivalent to 70m @ Ka-band
  - 240 Kbps from Neptune with an optical transponder of 75cm
  - 1 Mbps from Mars
  - Requirements based on a suite of 29 missions – 5 categories

GBATS - ATP Mechanism

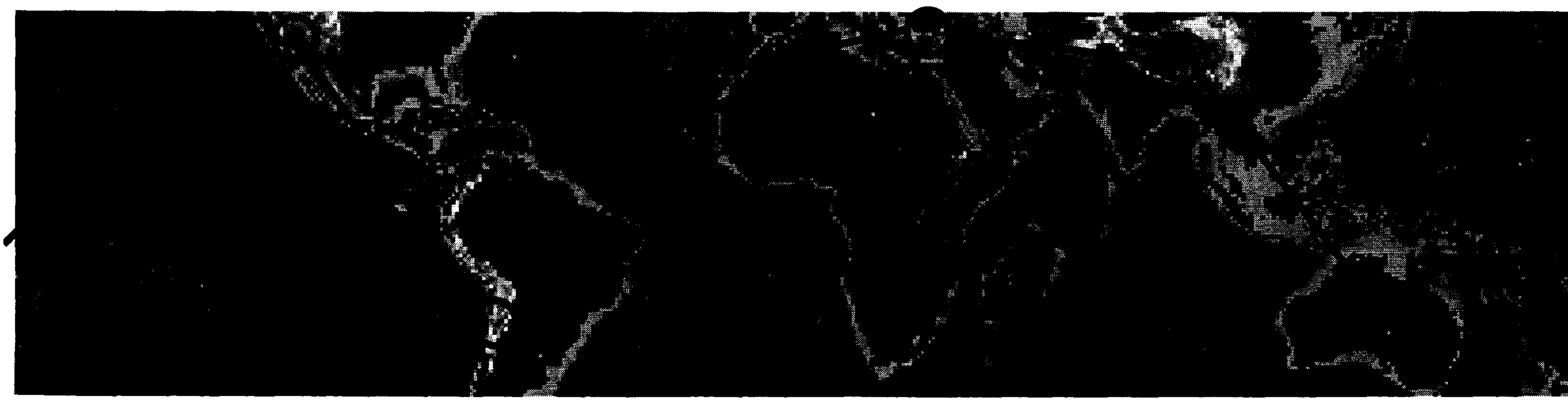


What Drives ODSN Architecture

- Two main factors:
  - Aperture size
  - Distance between stations (apertures)
- Earth Rotation & Weather Diversity (70% per station)
- Distance among stations (apertures)
  - Outage tolerance
  - Continuity in data stream
  - Operation cost
  - Minimum requirement on spacecraft
- Suggested GBATS Network Architectures
  - Linearly Dispersed Optical Subnet (LDOS)
  - Cluster Optical Subnet (COS)

Example of LDOS

- Ground Stations Distributed around the Earth in the Proximity of the Equator
- Ground Station Distance: almost Evenly Spaced
- Site Locations: Dry Weather, Weather Diversity, High Altitude
- Number of Stations: Depending of Issues of Global Coverage, Weather, etc.

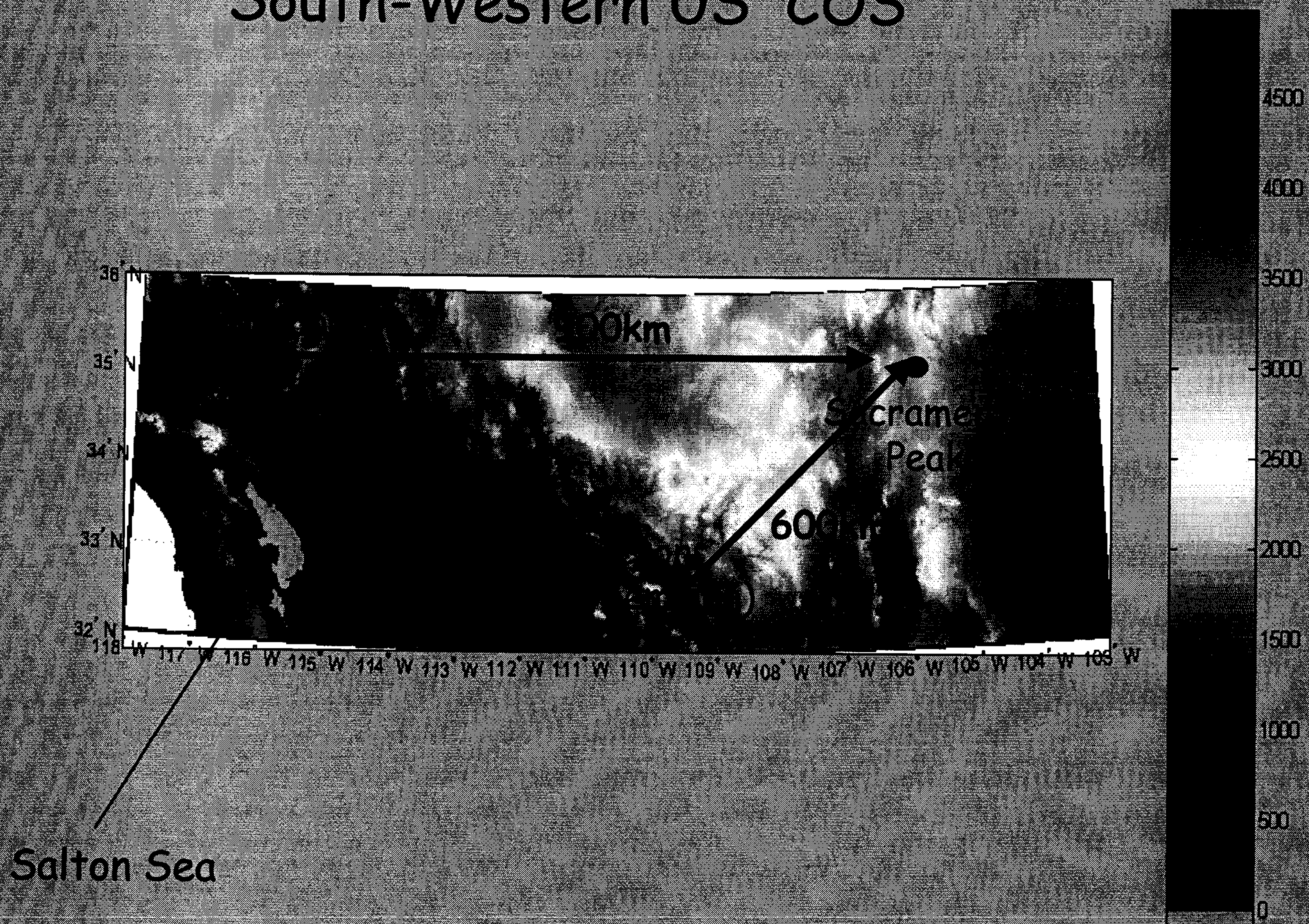


Global arrangement of seven ground stations in LDOS

Example of COS

- Three (or more) Clusters Evenly Separated on Earth
- Each Cluster (red circles) Composed of two (or more) Ground Stations (yellow stars) Located in Different Weather Cells
  - At least one Station in the Cluster has the highest probability to be Cloud Free
- Site Locations: Dry Weather, Weather Diversity, High Altitude etc.
- Number of Clusters: Depending of Issues of Global Coverage, Weather, etc.
- In the Figure: Cluster in the same region of today DSN

South-Western US COS



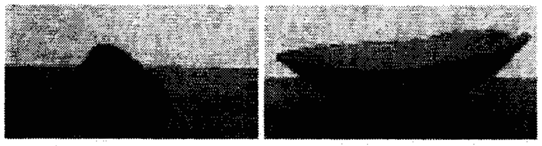
Site Selection Criteria for 10m Ground Station

- Reduction of the Atmospheric Effects
  - Low Cloud Coverage (high probability of clear sky)
  - Dry weather (e.g. South Western US)
  - High Altitude, preferably mountain tops to reduce: Atmospheric Path Absorption, Clear air turbulence Haze and aerosol scattering, Sky Radiance and Urbanization Related Light Pollution
- Efficient Sky Coverage
  - Within +/- 40° Latitude
- Infrastructure and Maintenance Cost Reduction
  - Accessible Locations, Existing Infrastructure, Controlled Access and Security
- Geopolitical Issues
  - Especially when considering Locations Outside US
- Eventual Integration in an Optical Subnet
  - Adjacent Stations Should be localized in different Climatic Zones
    - Distance defines the COS distance
  - Ground Station Spacing: the Subnet must provide a 24 hours a day line-of-site coverage

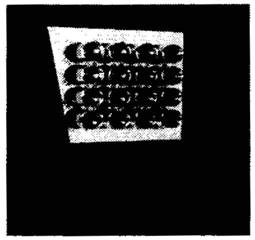
Technology Trends Since GBATS - 1994

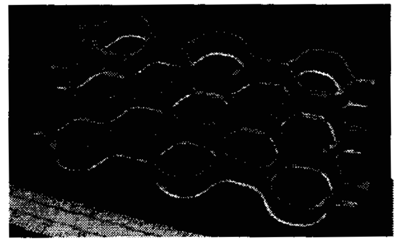
- Aberration correction methods
  - Wavefront sensors
  - Edge sensors
- Miniature mirror actuators with memory states (DSP, or Laser Driven)
- Detector arrays
- More accurate Weather Databases
- Optical phase shifters
- Optical arrays (VLT, ELT)
- Advances in space telescopes (From 240 km/m^2 to 15km/m^2)
- Internet Satellite Era for Global coverage
- Experience with existing 10m telescopes (HET, Keck)
- RF arrays (Uplink & Downlink)
- Structural materials (synthetics, inorganic, reactive LC)
- Shaped memory polymers & dynamic modulus composite materials
- Coaxial ATP & Communication
- Multiple vendor experience with large apertures

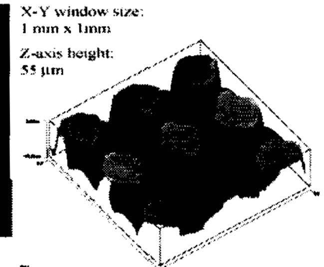
Changes Since GBATS - Examples

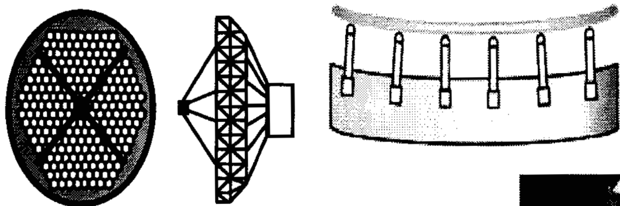


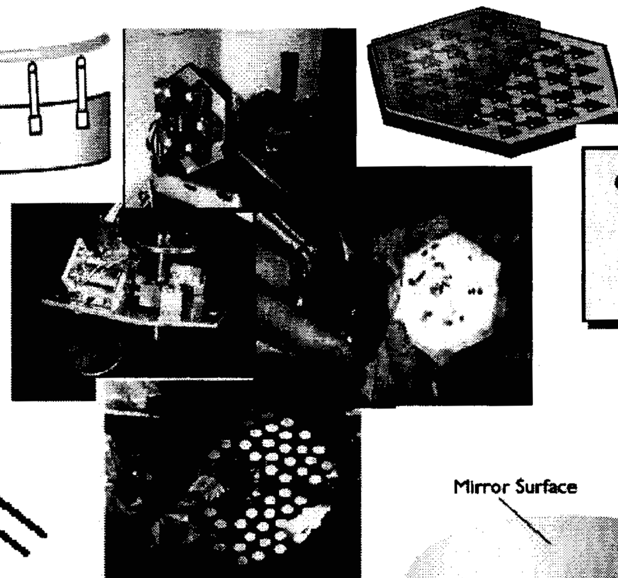
Rolled SMP reflector unfurls to near-net shape.



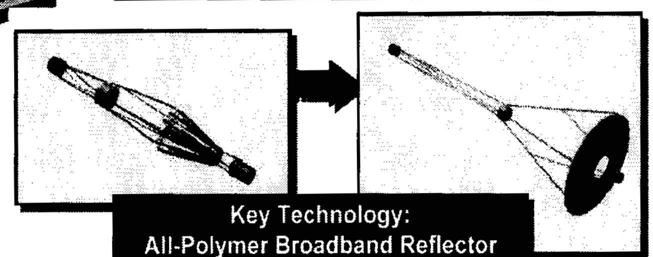








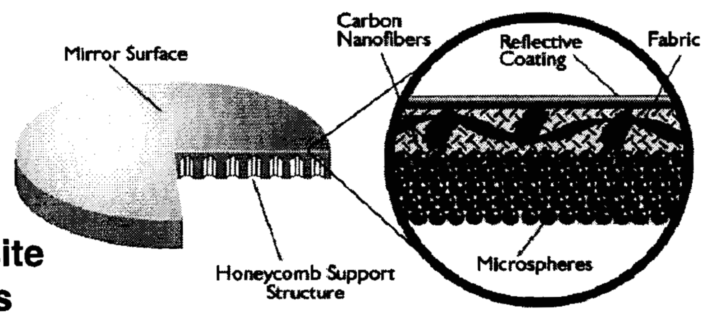
Phase Corrector with Partially Flattened Microactuators



Key Technology:
All-Polymer Broadband Reflector

Shape Memory Polymer optical phase corrector provides post-deployment wavefront correction.

Composite Mirrors



Example Changes in High Level Requirements

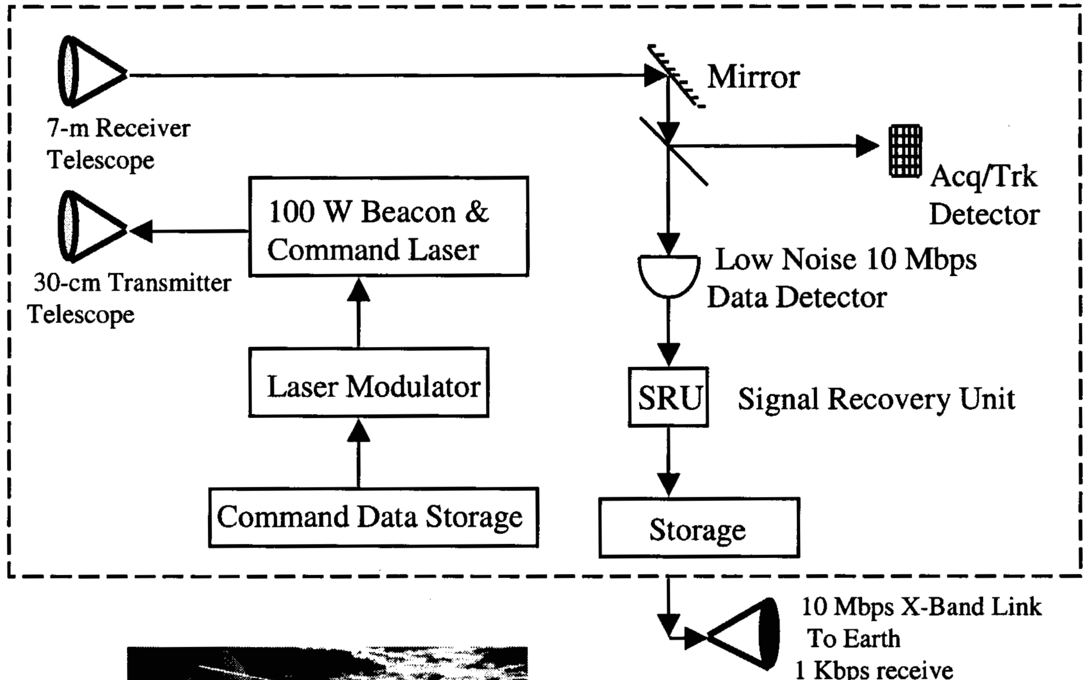
- LDOS & COS design was based on Ka-band 70m capability
- New Ka-band network availability shifted from 90% to 95%
- Minimum elevation angle changed from 15 to 20 degrees
- Minimum Sun-Earth-Probe (SEP) angle changed from 10° to 5°

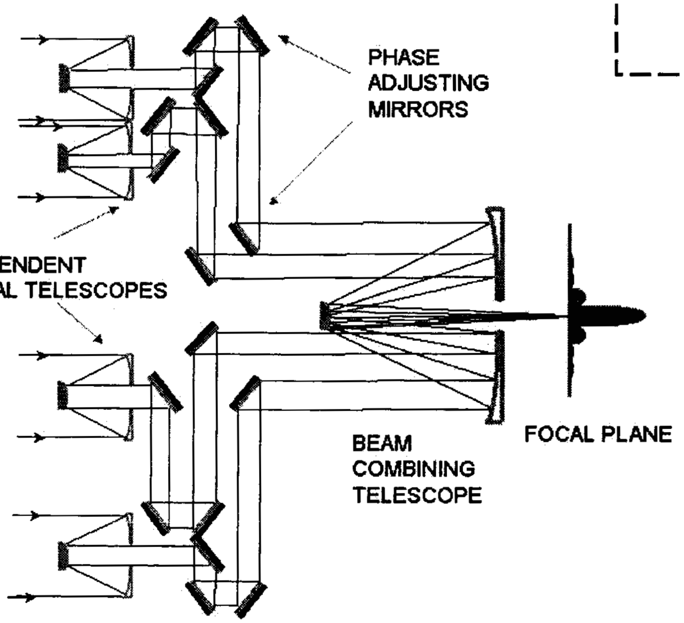
Optical Mission Needs

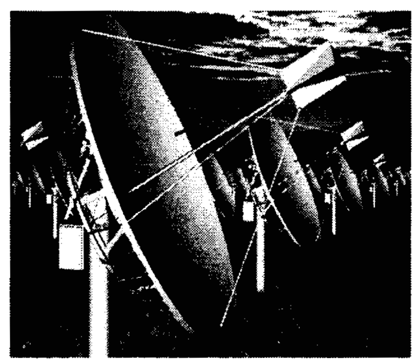
- GBATS was based on single spacecraft in deep space
- Special emphasis was given to Mars to drive Operation concept
- Optical missions heavily dependent on link geometry
  - LOS & Cloud coverage, handover
- GBATS lacks the ATP & Communication trades
- GBATS did not consider examples of Optical missions
- GBATS did not consider formation flying
  - Orbital management of cluster of spacecrafts
- Optical missions still dependent on RF (e.g., Emergency)
- In orbit optical sensor networks need to be considered
- Optical mission suite needs to be defined & exemplified

New Architectural Solutions

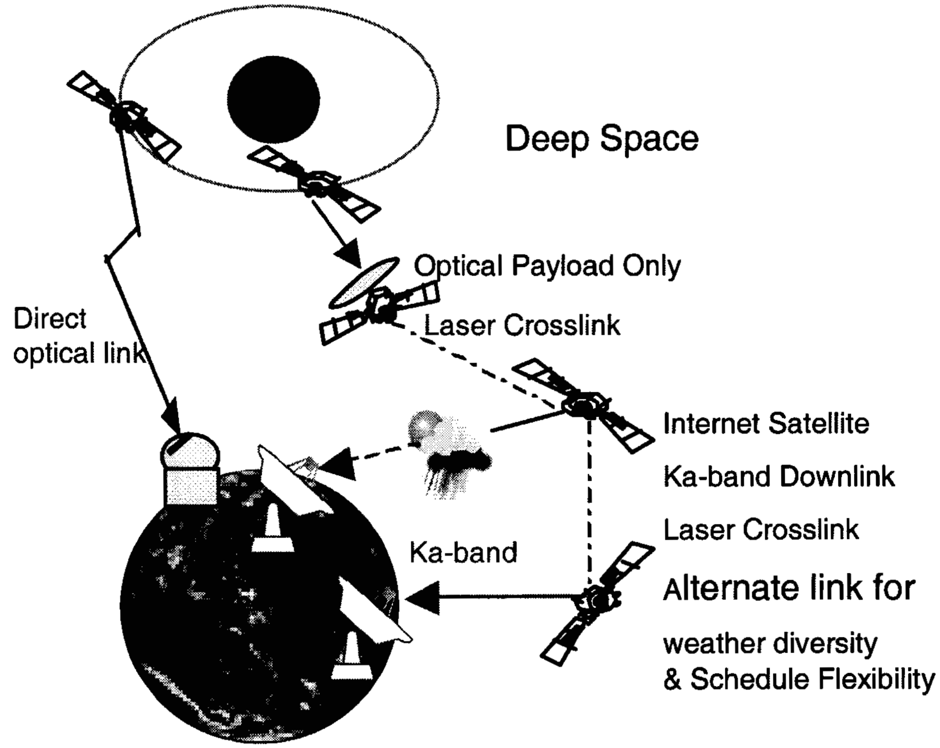
- Array small apertures
- RF Array large apertures
- Optical arrays
- Hybrid ground-space
- Hybrid RF/Optics
- Using Internet Satellites







Making Use of Internet Satellites



- Assure Global Coverage
- Internet Satellite to Provide Network Services
- Internet Satellite Constellation to Provide Weather Diversity

ODSN Cost Estimation Methods

- Parametric Approach
  - Different to generate for architectures of different natures
  - It does not take into consideration changes over time of the different cost factors
  - Errors in historical data can generate large final cost errors
  - Lack of sufficient data for large aperture telescopes
- Design to Cost (DTC)
  - Targets cost reduction of Life Cycle Cost (LCC)
  - Incorporated in early conceptual assessment of the architecture
  - Need of multiple design options at the early stage of the architecture conception: optimization of figure of merits point towards the better design option

Life Cycle Cost (LCC)

- Reduction of the architecture cost is based on the operation and maintenance over time
  - Large Aperture Astronomical telescopes
    - Yearly operation cost 3%-6% of the construction cost
    - Yearly maintenance and upgrades 3%-5% of the construction cost
- ODSN is unprecedented: learning from the DSN
  - Goldstone 70m antenna operational for 36 years so far, with an extension of 25 years
  - ODSN probable life extension of 50 years
- ODSN Operations
  - Telescope(s) and Control Station(s) Separated
    - Cost Advantage
  - Telescope easily accessible from the Control Station for Maintenance
    - Proximity Control Station to Telescope reduce operator travel time

Facility Impact on Cost

- Functional Requirements of ODSN facility
  - Shelter and Storage; Facilities; Environmental Control; Protection and Safety; Access
- ODSN facility construction
  - Easy access to support facility of heavy equipment and material
    - Not trivial when the facility is on mountain top
  - Temporary Shelter for operators and workers will be necessary
  - Proximity from existing site that support material delivery
  - Other Political issues need to be considered
    - Licenses, Permits, and use of local human resources
- ODSN operation
  - Self Contained Sites, storage of water and fuel
  - Emergency conditions when access not possible to the stations
    - Storms, snow, and other meteorological factor that can impact mountain tops
    - Climate conditions of the site need to be assessed also to consider this issue

CONCLUSION

- GBATS was the first attempt to introduce ODSN in 1994
- GBATS approach was mostly heuristic, i.e., no cost methods
- The envisioned architectures in GBATS were useful but costly & heavily dependent on high altitude peaks that are hard to find

- ODSN is hard to envision without RF assistance
  - e.g., emergency situations, data distributions, network interfaces

- Need to have Optical Mission Suite to derive new ODSN requirements
  - ODSN heavily driven by link geometry

- Need to formulate figures of merit to compare candidate architectures at functional levels, early in design concepts through DTC method

- Optical arrays, Internet Satellites, and hybrid RF/Optics shall be considered and compared through figures of merit in order to achieve a solid design that meets the cost ceilings of ODSN

- Need to find stakeholders for ODSN to further share resources and therefore reduce the cost