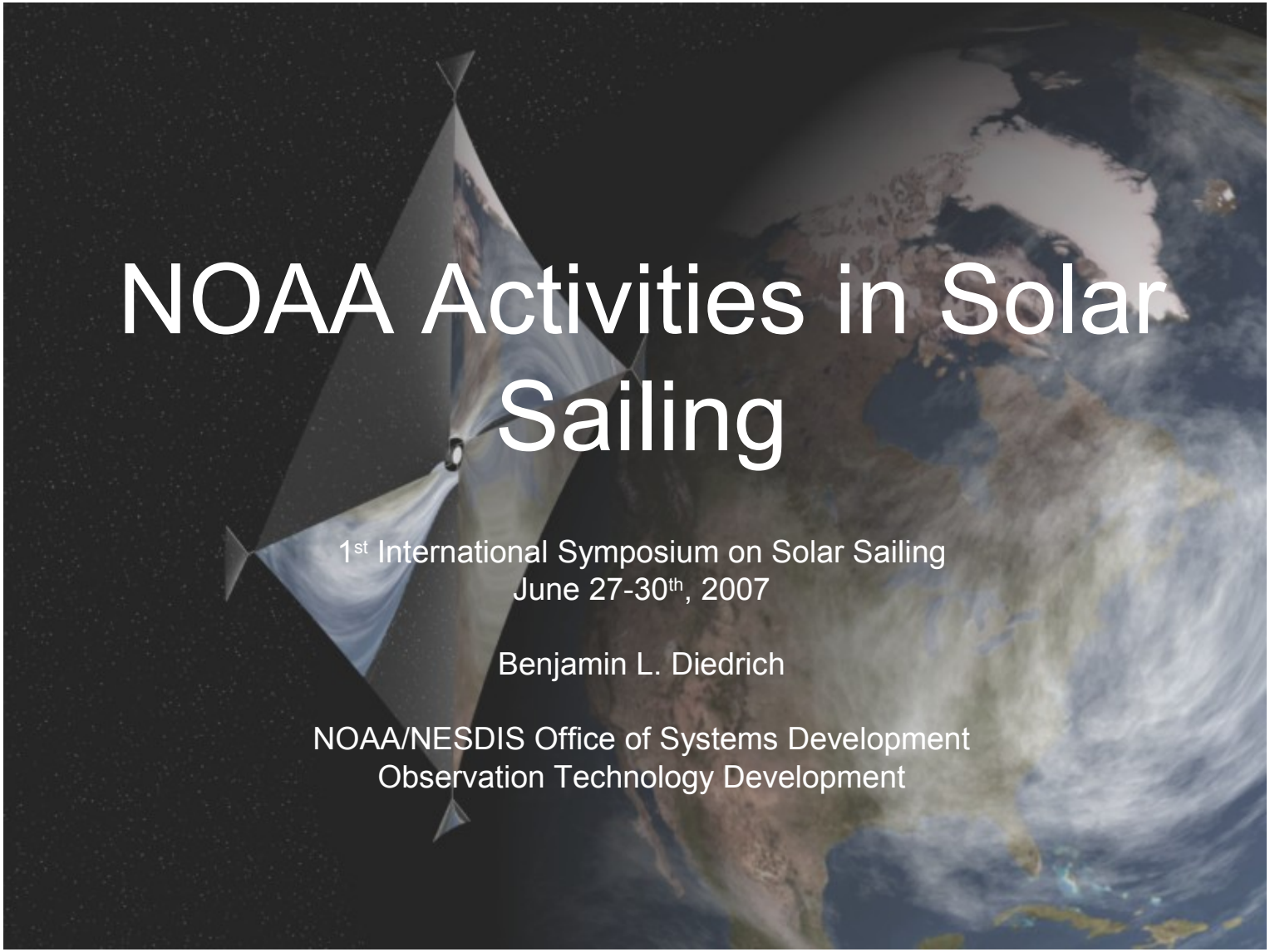


NOAA Activities in Solar Sailing

1st International Symposium on Solar Sailing
June 27-30th, 2007

Benjamin L. Diedrich

NOAA/NESDIS Office of Systems Development
Observation Technology Development

Summary

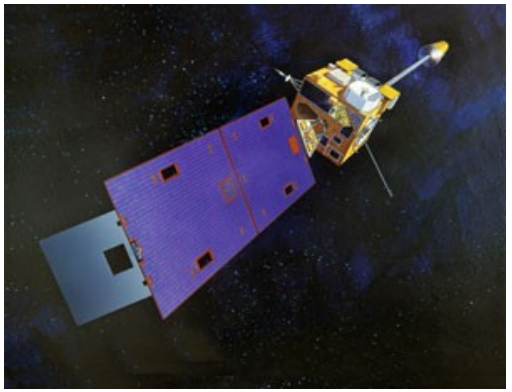
- NOAA
- History
- Artificial Lagrange Orbits
  - Applications & Benefits
- Activities
  - Space Weather
  - Communications
  - Remote sensing
  - Technology

National Oceanic and Atmospheric Administration

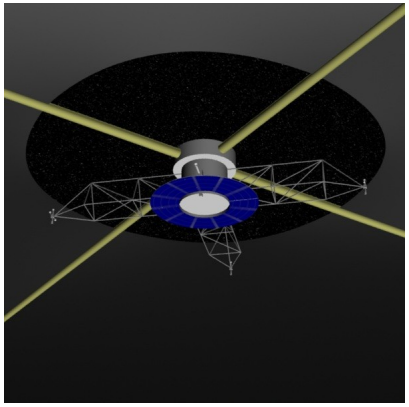
- Federal agency in the U.S. Department of Commerce focused on the oceans and atmosphere
  - Environmental information products
  - Environmental stewardship services
  - Applied scientific research
    - Ecosystems
    - Climate
    - Weather & Water
    - Commerce & Transportation
- National Environmental Satellite, Data and Information Service (NESDIS)
  - Operational environmental satellites
  - Data & Information
  - Research
- Technology, Planning, & Integration Office, Observation Technology Development
  - Maintains database of all NOAA observing requirements and observing systems
  - Analysis of observing system architectures
  - Develop new satellite technologies & architectures to improve observations and provide real-time, global, polar Earth coverage.
    - Medium Earth Orbit (MEO), Molniya, Lagrange and Artificial Lagrange Orbits (LOs/ALOs)
    - GEO/MEO microwave sounding
    - Data compression
  - Partnership opportunities with new satellite architectures
  - Commercial procurement of satellite services

History

- GOES I-M “Solar Sail”
  - Momentum management with solar sail boom & solar array trim tab
- Geostorms
  - Proposed joint NOAA/NASA/Dept. of Defense (DoD) mission to monitor the solar wind from a sub-L1 orbit and demonstrate solar sail technology.



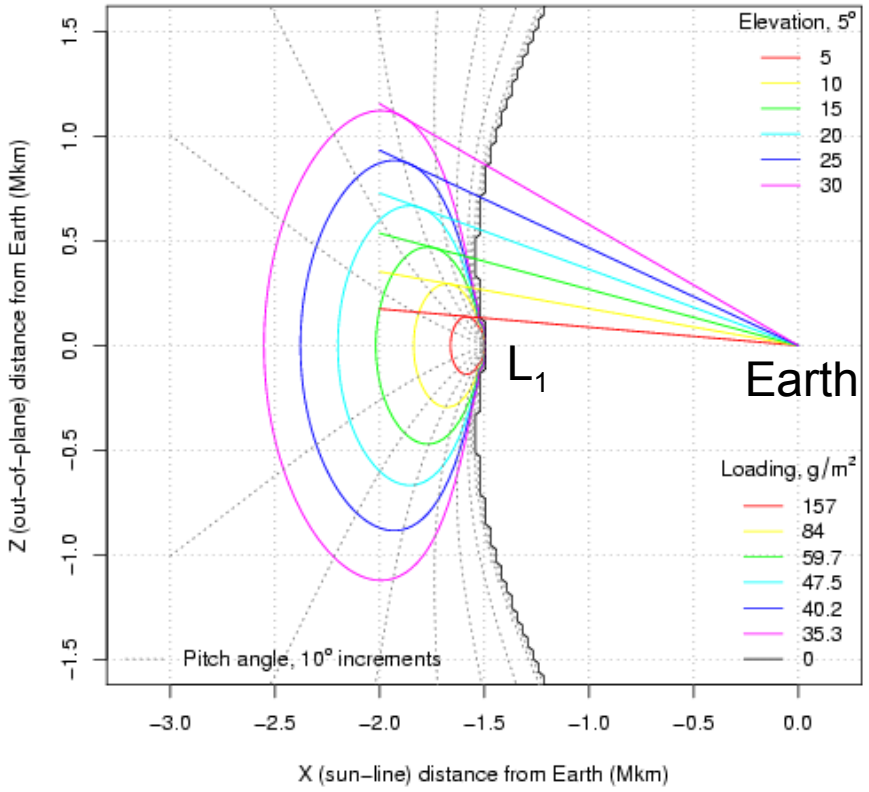
GOES I-M solar sail & trim tab



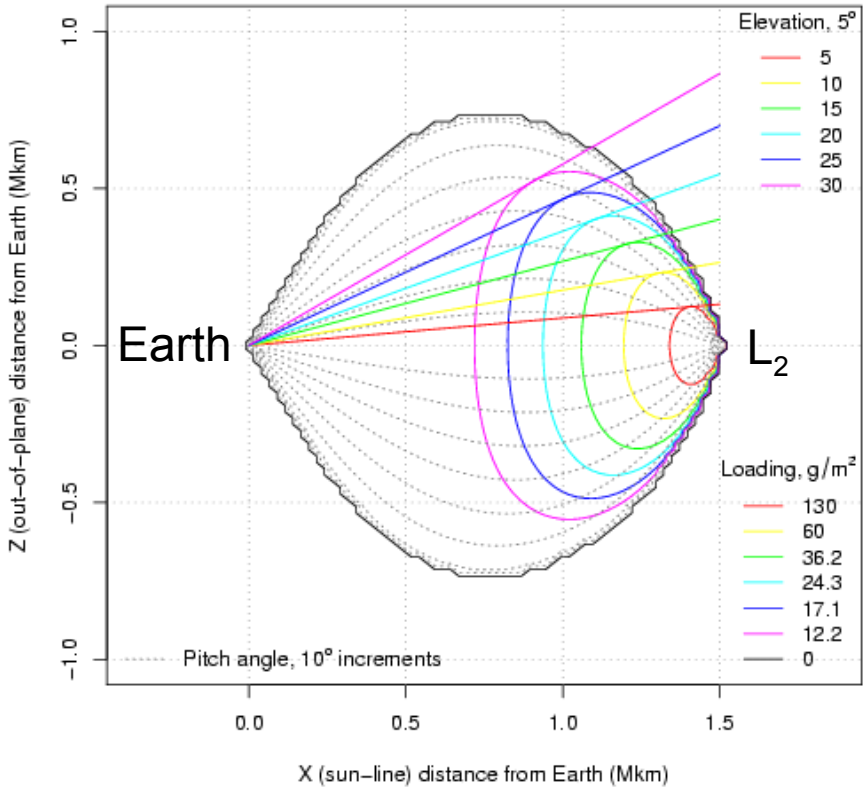
1999, JPL/L’Garde ST-5 Geostorms

Artificial Lagrange Orbits (ALOs)

L_1

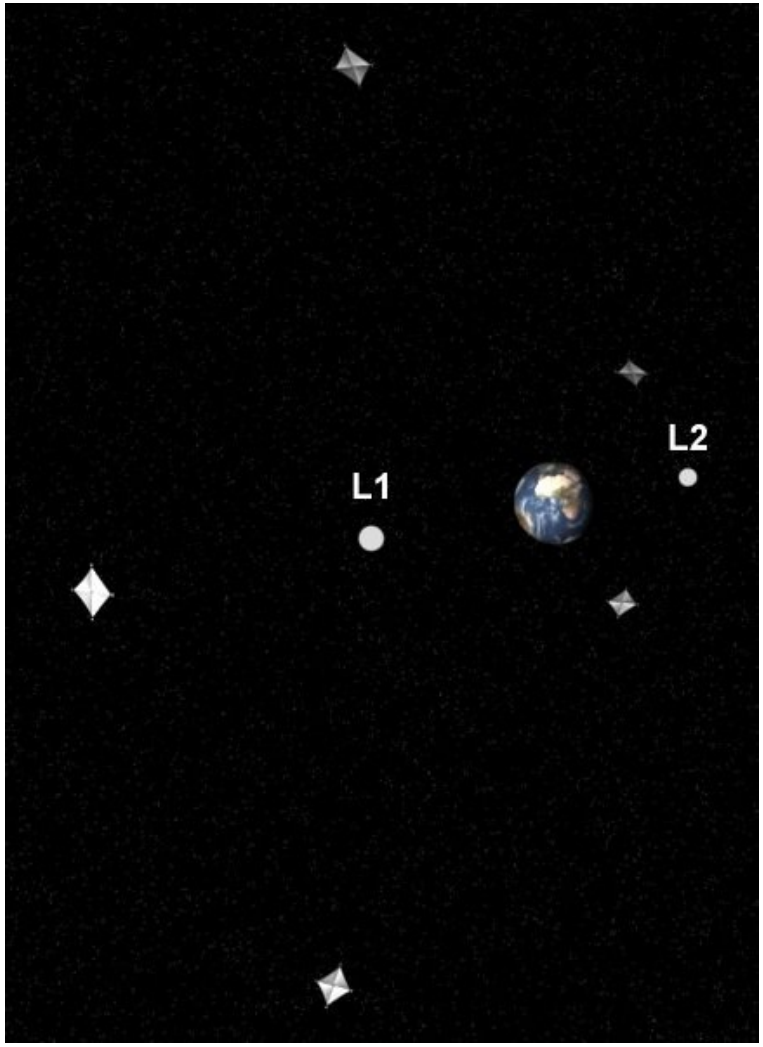


L_2



ALO Applications & Benefits

- Space weather
  - Solar wind monitoring (sub L1)
  - Solar observation
  - Ultraviolet polar auroral imaging (N/S L2)
  - Radio beacon ionospheric scintillation
- Communications
  - Satellite crosslink
  - Polar communications (N/S L1 or L2)
  - Space exploration
- Remote sensing
  - Hemispheric, real-time, polar
  - Lunar calibration
  - Stable thermal and dynamic environment
  - Relatively benign radiation environment
  - Constant illuminated / shadowed Earth view
  - Constant solar scattering angle
  - Reasonable resolution
  - Several data products identified
    - Earth radiation budget, total & spectral solar irradiance, aerosols, clouds, sea surface temperature, winds, carbon gases, ozone, aurora, ionospheric scintillation



Activities

- Space Weather
- Communications
- Remote Sensing
- Technology

Space Weather
Solar wind

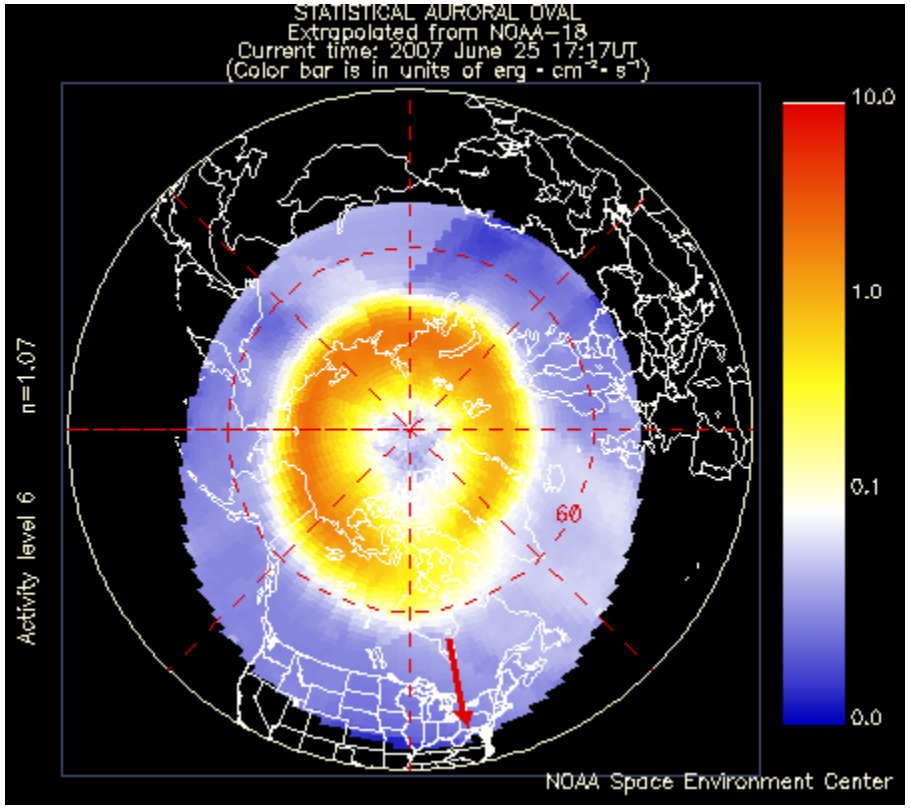
- NASA's Advanced Composition Explorer (ACE) monitors solar wind from L1 orbit and sends realtime date to NOAA's Space Environment Center (SEC). 1997 launch. Well past design life.
- Disturbances cause geomagnetic storms ~30-60 min later when they reach Earth, disrupting electric power distribution, GPS, and HF communications.
- Solar sail stationed sunward of L1 increases warning time proportionally.
- NOAA is working on an operational follow-on to ACE.
  - Request for Information
  - Broad Agency Announcement (BAA) studies
    - Space Services Inc
      - Commercial solar wind service from solar sail small satellite in sub-L1 ALO
    - Lockheed Martin
      - Government solar wind small satellite
      - Refurbish Deep Space Climate Observatory (DSCOVR, formerly Triana)
  - Preferred option
    - Commercial solar wind data service with DSCOVR as 1st element in ongoing architecture

Space Weather
Solar observation

- Solar imaging & radiometry
- LO/ALO spacecraft ideal platform. Dynamic & thermal stability and constant solar visibility.
- Coronal Mass Ejection (CME) imaging
  - Plasma eruptions from solar corona that reach Earth ~1-3 days, leading to geomagnetic storms.
  - Coronagraphs and heliospheric imagers spot CMEs leaving sun and transiting to Earth. Solar wind measurement still required for forecast and strength.
  - NASA/ESA SOHO & NASA STEREO available.
  - NOAA BAA also funded two CME imaging concepts
    - Naval Research Lab Compact Coronagraph (CCOR)
    - Southwest Research Institute (SwRI) Dual-Acquisition Miniature All-Sky Coronagraph (DAMASC)
- Solar X-Ray/UV imaging
  - Identify solar features and flare locations
  - NOAA GOES, SOHO, STEREO
- X-Ray/Extreme UV sensors
  - Total solar X-ray and extreme UV output.
  - Flare alerts & magnitude, thermosphere & ionosphere modeling
  - NOAA GOES

Space Weather Auroral Imaging, Ionospheric Scintillation

- Auroral Imaging
  - Currently provided by UV imagers on polar-orbiting Defense Meteorological Support Satellite (DMSP). Removed from planned NPOESS instruments.
  - UV imager on north or south L2 ALO satellite observes aurora over polar hemisphere continuously.
- Ionospheric scintillation
  - Currently provided by COSMIC science mission using GPS scintillation.
  - Radio beacons on ALO satellites with ground receivers in polar regions allow polar region measurements.



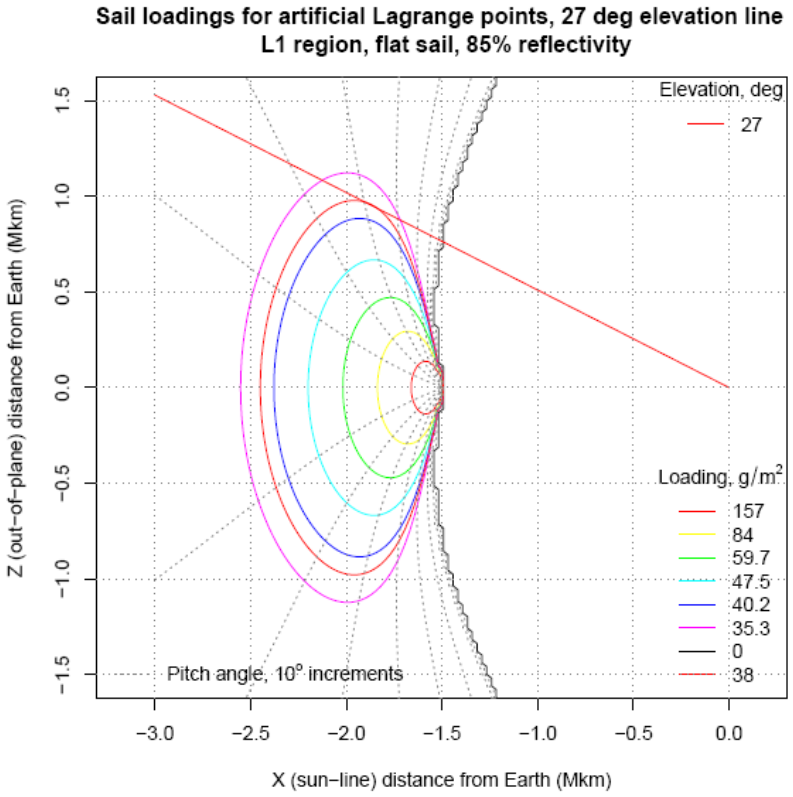
Auroral Oval from DMSP UV imaging
NOAA Space Environment Center

Communications
Polar orbit crosslink

- Polar environmental satellites (NOAA, NASA, Dept. of Defense, EUMETSAT) use ground stations for downlink. Data latency can be long.
- National Polar-orbiting Operational Environmental Satellite System (NPOESS) plans to use 15 ground stations (SafetyNet).
- Crosslink through communication satellites in LOs & ALOs greatly reduces ground infrastructure for near real-time data latency.
- Two satellites in opposite LOs or ALOs have visibility to all satellites in Earth orbit.

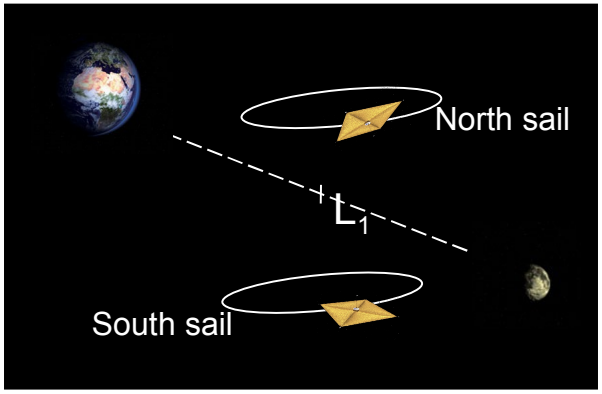
Communications
South pole communications

- National Science Foundation (NSF) operates the South Pole research station. Limited communication coverage (several hours per day) from old geosynchronous satellites in inclined orbits.
- A single ALO satellite >22.5° south of L1 or L2 has year-round visibility to the South Pole. Remaining close to the sun-Earth line also permits solar wind monitoring.

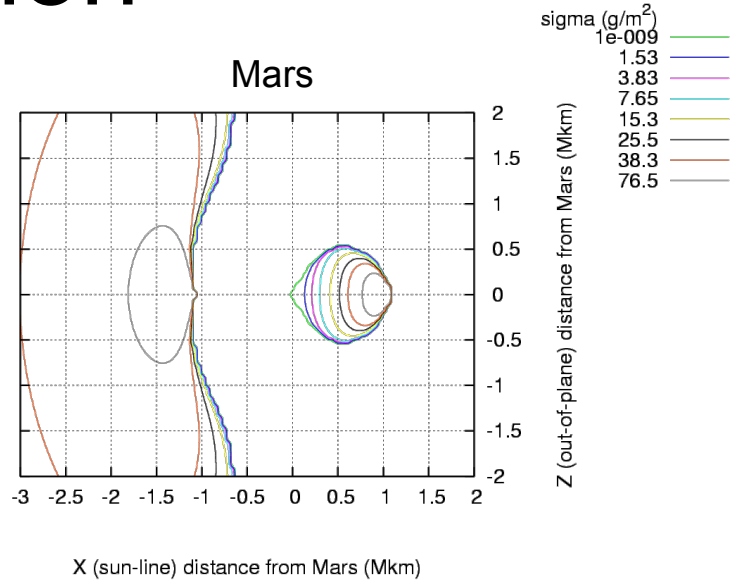


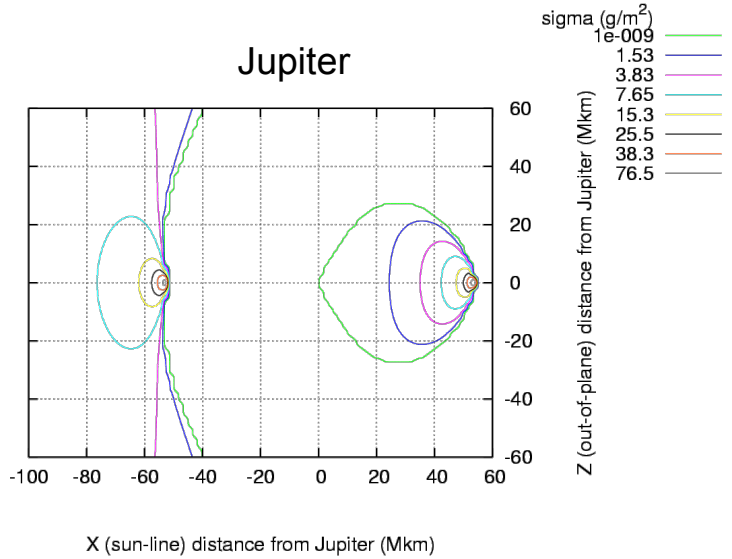
Communications Exploration

- ALOs with visibility to Earth's poles also view the Moon's poles.
- ALOs at Mars are lower altitude and higher elevation angle than comparable sails at Earth due to lower gravity.
- The sun periodically blocks communications between Earth and Mars. Very high elevation spacecraft may be able to close this link.
- ALOs will work at Jupiter, but at higher altitude and lower elevation angle due to higher gravity.
- Sail-modified Earth-Moon Lagrange orbits may permit shorter range Lunar surface communications.



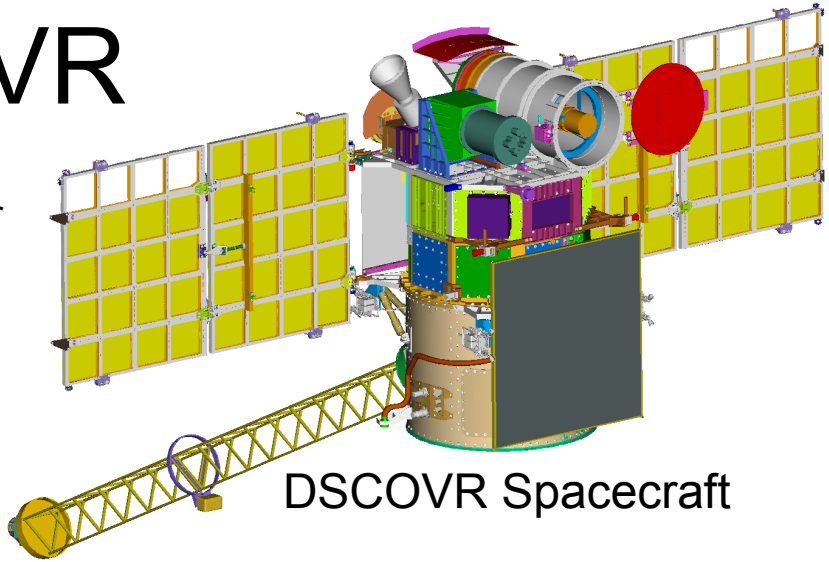
Sail-modified Earth-Moon Lagrange orbits
Prof. Colin McInnes



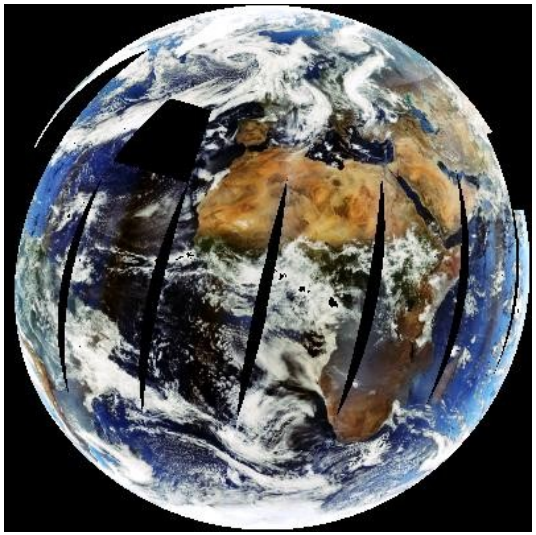


Remote sensing DSCOVR

- Remote Earth sensing from L1 orbit
  - Near IR to UV imager: Earth Polychromatic Imager (EPIC), 8+ km resolution, 317.5-905 nm
  - Broadband radiometer: NIST Advanced Radiometer (NISTAR)
  - Solar wind
- Earth science data products
  - Ozone, SO_2, Aerosols, clouds, vegetation, precipitable water, Earth radiation budget
- Excellent temporal & spatial coverage.
  - Observes sunlit hemisphere of the Earth over daily and seasonal variation
  - Fills in polar & geostationary gaps
  - Polar view in winter (south) and summer (north)
- Lunar calibration every month
- Numerous coincident observations on Earth, in air, and in orbit for calibration
- Stable dynamic & thermal environment
- Near-constant solar scattering angle
- Unique Earth perspective whose scientific and operational benefits have not yet been demonstrated.



DSCOVR Spacecraft



Simulated DSCOVR view with NASA MODIS data

Remote Sensing ALOs

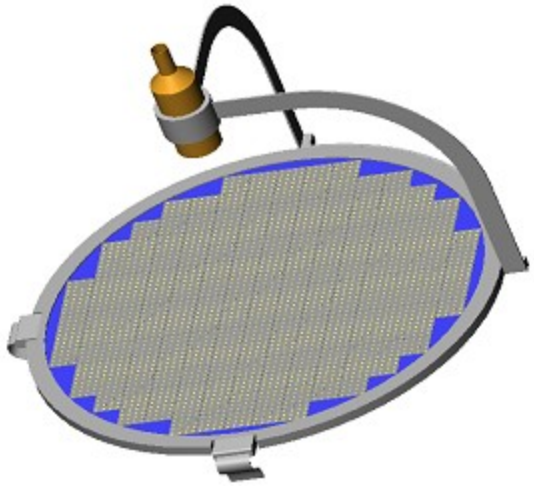
- All the benefits of DSCOVR (LO) with year-round polar coverage.
- Global coverage from 2 opposite (N/S, L1/L2) ALOs.
- Custom designed instruments may provide many more data products
  - Earth radiation budget
  - Total & spectral solar irradiance
  - Aerosols
  - Clouds
  - Sea surface temperature
  - Winds
  - Carbon gases
  - Ozone
  - Aurora
  - Ionospheric scintillation

ALO view in winter

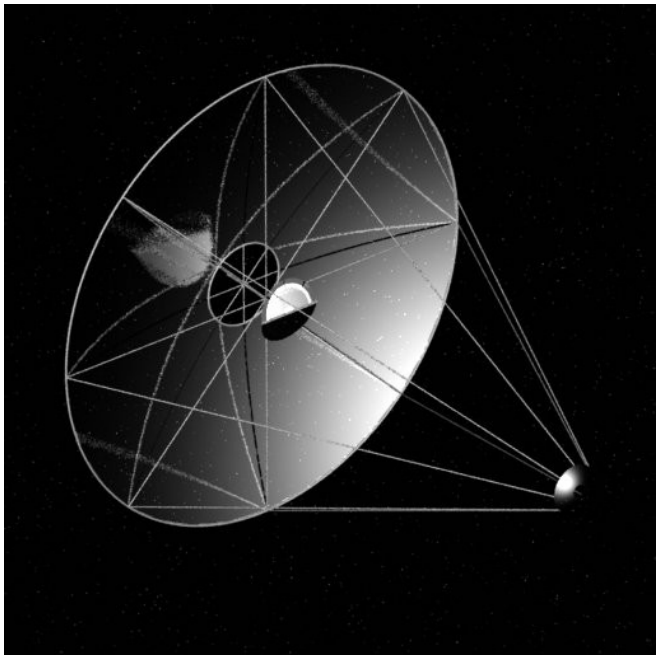
ALO view in summer

Technology

- Engineering data buy
  - Private technology development by L'Garde Inc for Team Encounter into 0.9 micron Mylar sails and lightweight inflatable booms.
- Solar sail mission requirements
  - Various studies of the minimum ALOs required for a variety of missions.
  - South pole comm combined with solar wind, Lunar comm, Mars solar eclipse communication
  - Comm system requirements (size, power, frequency) for a variety of communication missions
- Sail integrated reflactarray
  - Discussions with JPL and NASA. Planar array of small antenna elements that emulate a shaped (e.g. parabolic) antenna based on element phase. Large, lightweight structure that may be compatible with sails. Beam steering possible to point independent of sail.
- Comparison with other propulsion technology
  - Can sails be replaced or work in conjunction with other propulsion technologies in maintaining ALOs? Not competitive due to mass, cost, lifetime, and technology maturity. Beamed propulsion may enable new ALOs, but at high cost and technology.
- Compound solar sails
  - Parabolic mainsail always points towards the sun, collecting sunlight and focusing it on a smaller, steerable optics system to reflect the sunlight in the required direction for thrust generation. Cosine thrust loss from solar off-pointing instead of cosine-squared. More efficient at assuming ALOs.
- ALO plotting tool
  - Solves McInnes' equations for ALO equilibrium points with partially reflective sails. Includes compound sails.



Reflectarray (NASA)



Compound sail concept (NOAA)

Acknowledgements

- Space Services Inc.
- Team Encounter
- L'Garde
- Ball Aerospace
- Raytheon
- JPL
- Titan, SM Resources Corporation
- Lockheed Martin
- NASA Space Communications Architecture Working Group
- Prof. Colin McInnes
- Aerospace Corporation
- Scripps Oceanographic Institute
- Southwest Research Institute
- Naval Research Lab
- NASA Glenn Research Center