Observational Architectures for Enabling Earthquake Forecasting

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20-Year Vision

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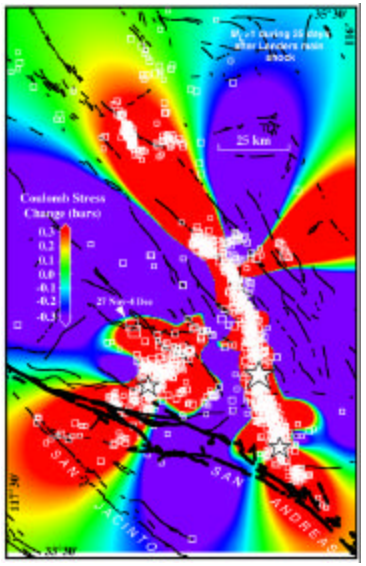
To enable accurate, timely earthquake forecasting to mitigate structural failures and reduce human and economic impacts of large earthquakes

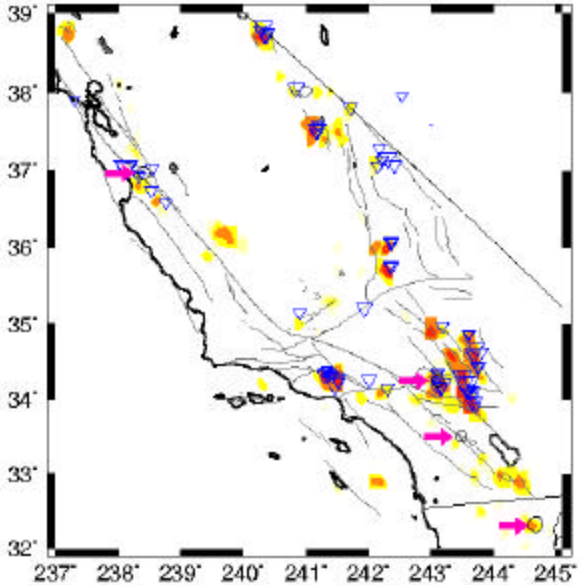


Understand earthquake physics globally

- Time-dependent models of crustal deformation
- Stress maps with frequent updates

Develop accurate and timely forecasting capabilities

- Monthly hazard assessments for interacting fault systems
- Predict stress transfer and triggered seismicity
- Assess shaking and landslide vulnerability



Provide effective disaster management

- Improve building codes
- Prioritize retrofitting projects
- Rapid damage assessment
- Revise stress maps and hazard assessments

High Temporal Resolution InSAR is Required

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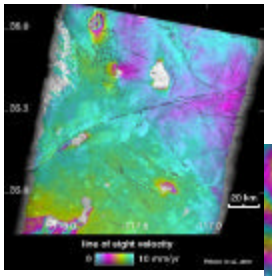
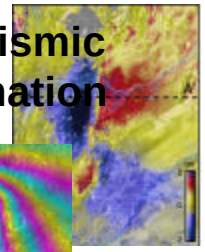
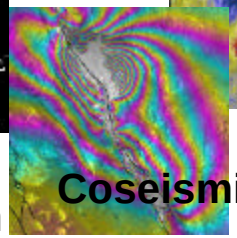
Spatial Coverage: Continuous — Discrete



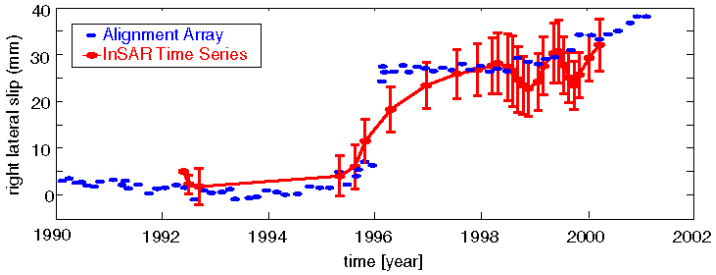
Interseismic deformation



Postseismic deformation

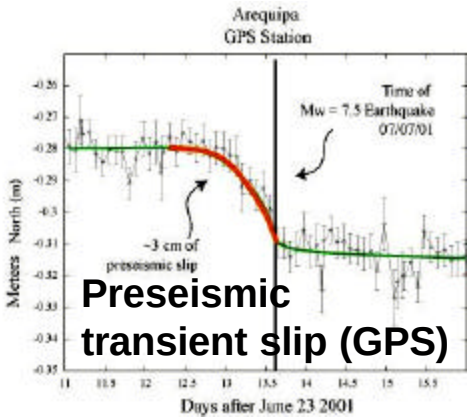


Coseismic rupture



InSAR time series

- Surface Deformation is Key Observable from Space



Preseismic transient slip (GPS)

Seismology

Discrete — Continuous

Temporal Coverage

Observations to Prediction

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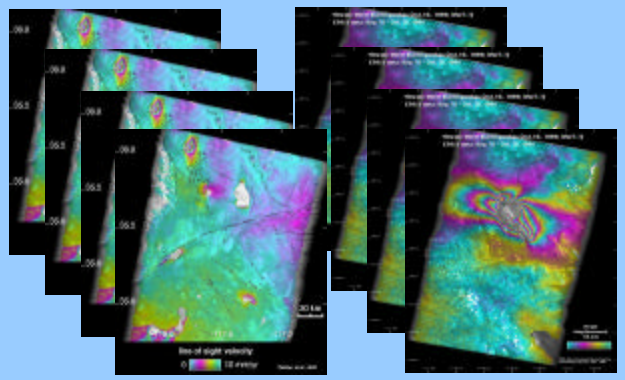
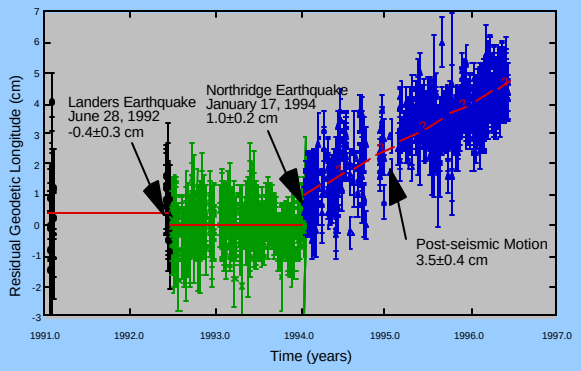
Surface Deformation

– *InSAR time series*



– *GPS time series*



– Seismicity

Community Modeling Environment

- General Earthquake Model (GEM) is prototype
- SCEC community model
- Included in Solid Earth Real-time Virtual Observatory (SERVO)

Dynamic Earthquake Hazard Assessment

(monthly to annual/USGS)

- FEMA
- CA OES
- Urban planners
- Insurance Industry

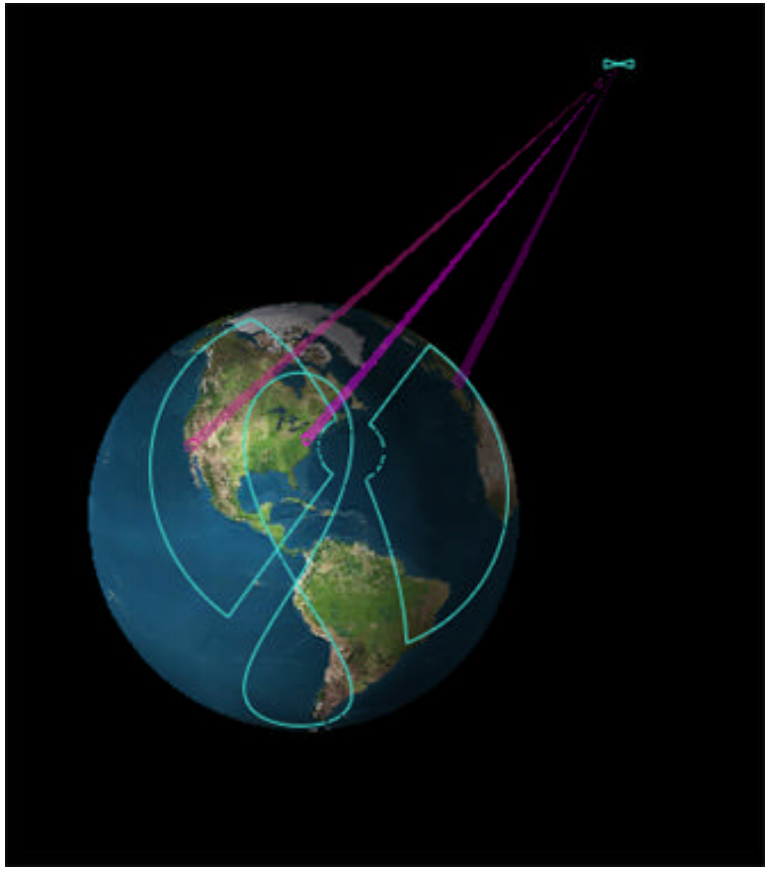
Driving Mission Requirements

- **Measurements of surface displacement:**
  - Interseismic strain requires long time series, very high displacement sensitivity
  - Transient and coseismic deformation and disaster response require high resolution and frequent access capability
  - Maintain maximum surface correlation → longer wavelength

	Minimum	Goal
Displacement accuracy (1–D)	25 mm instantaneous	5 mm instantaneous
3–D displacement accuracy	50 mm (1 week)	10 mm (1 day)
Displacement rate	2 mm/year (over 10 yr)	1 mm/year (over 10 yr)
Repeat period	**8 days**	**1 day**
Daily coverage	6×10^6 km^2	Global (land)
Map region	±60° latitude	Global
Spatial resolution	50–100 m	3–30 m
Geo-location accuracy	25 m	3 m
Swath	100 km	500 km
Data latency in case of event	1 day	Minutes-hrs

Geosynchronous SAR Accessibility

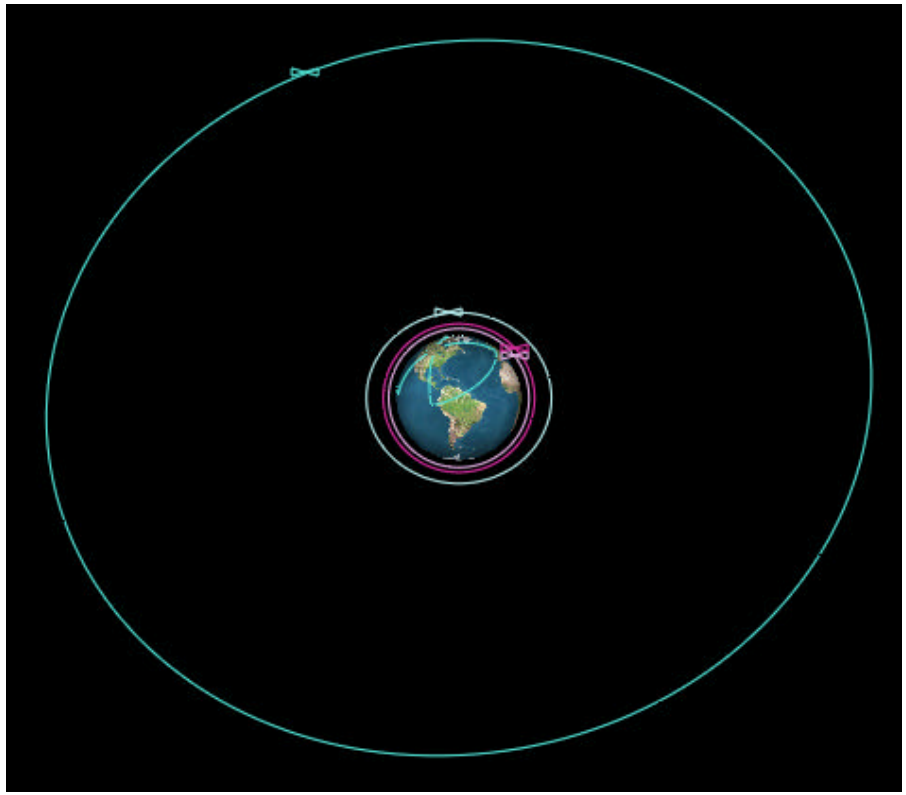
- No global coverage
- DC in view for 12 hrs, but also out of view for 12 hrs
- Increased performance for one area at expense of other areas (dwell on one area implies less data of other areas)
- Most useful if we know where interesting areas are



Advantages from Altitude

- Accessibility advantages of geosynchronous SAR come mainly from high altitude, not geosynch nature per se

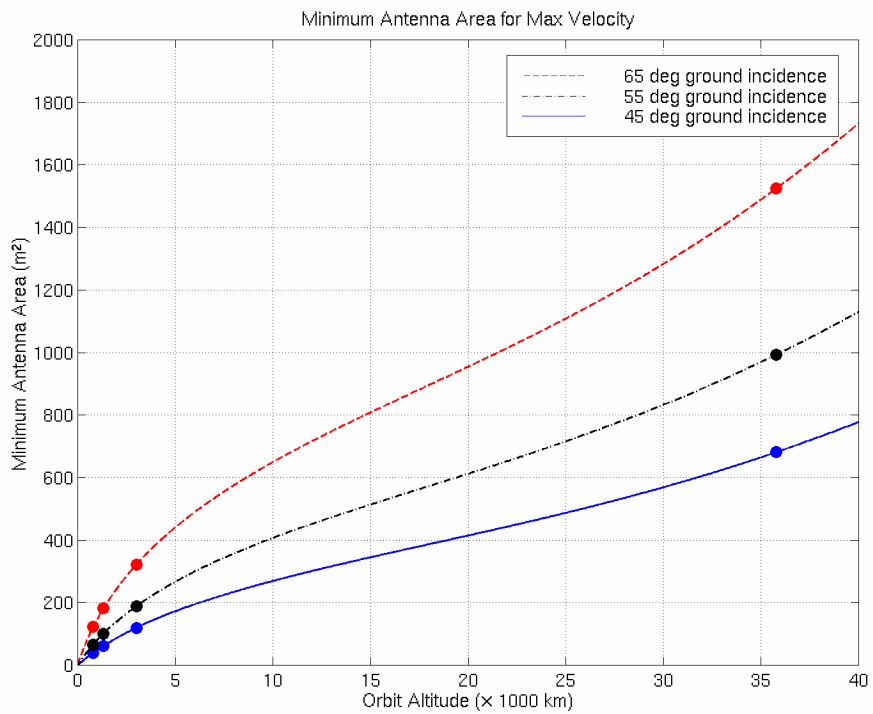
- High-altitude MEO may offer similar advantages



Minimum Antenna Area

- Fine spatial resolution can be attained even from very high altitude SARs
- However, still have minimum antenna area constraint due to range-Doppler ambiguities:

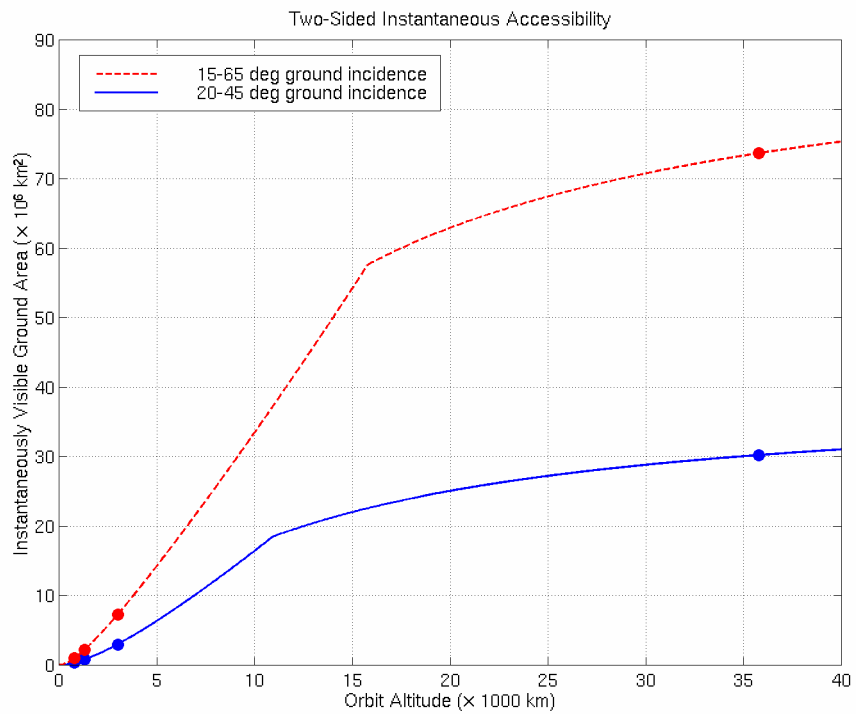
$$A \geq k \frac{4 r l v \tan q_{\text{inc}}}{c}$$



- High altitude SARs will require very large antennas, so lightweight antenna technologies needed

Footprint Area vs. Altitude

- Sensor footprint area grows with altitude
  - Limited by antenna steering capability at low altitudes
  - Limited by usable ground-squint angle at high altitudes
  - Note: Cannot necessarily acquire data from whole footprint simultaneously
- Sweet spot may be around 10–20,000 km (high MEO)



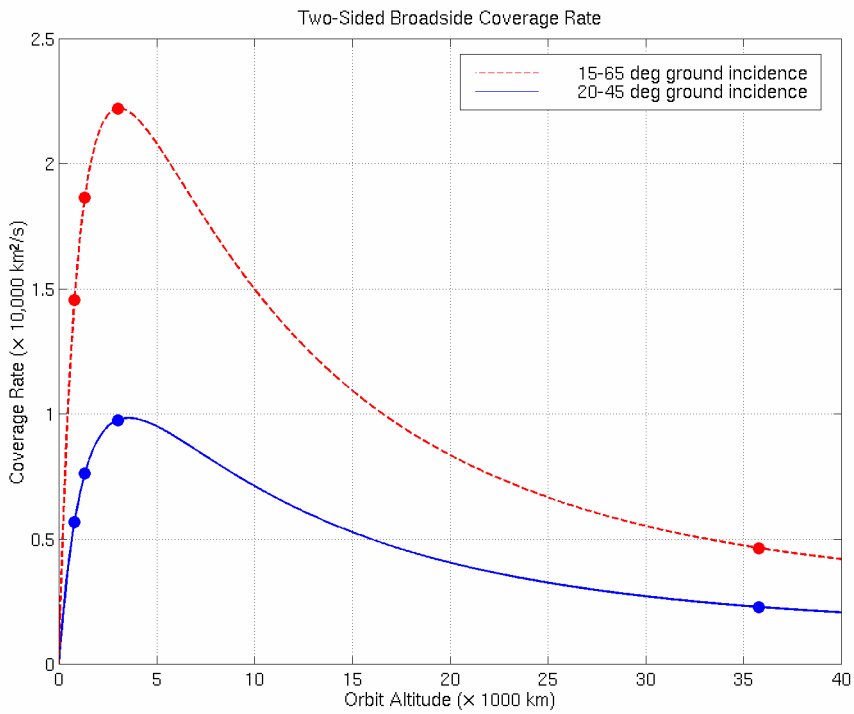
Shown: Two-sided sensor footprint area assuming ±15° azimuth beam steering and ±60° maximum ground squint

Repeat Period vs. Accessibility

- Accessibility of ground target from arbitrary angle is quantity of interest for standard imaging
- Temporal resolution of InSAR measurements also highly dependent upon orbit repeat period
  - Images comprising interferogram must be acquired from same viewing geometry
  - Effective repeat period can be reduced with multiple spacecraft following same ground track
  - Greater accessibility *may* imply shorter repeat periods
  - Multiple interferometric pairs from different viewing geometries can be averaged (stacked) for greater accuracy

Accessibility Rate

- Footprint area is static quantity
- Accessibility rate is perhaps more indicative of InSAR performance
  - Multiply swath width by nadir-point velocity
  - Roughly proportional to orbit-average accessibility, rather than instantaneous accessibility
- Optimal altitude around 3000 km (low MEO)



Shown: Two-sided accessibility rate, assuming broadside acquisition only (nadir-point velocity averaged over orbit)

MEO Design: Altitude Trades

- Accessibility rate peaks around 3000 km altitude
  - Assumes coverage limited by ground incidence angle
  - Assumes antenna area and steering sufficient
  - Capability for 24-hour accessibility not considered
- If antenna area fixed, coverage better at lower altitudes
- Altitude trades for 2500–5000 km regime:

	Lower Better	Higher Better	Notes
Accessibility rate (antenna area fixed)	X		Slow effect
Antenna steering requirement		X	Slow effect
Launch mass margin	X		Slow effect
Ground station visibility		X	Slow effect
Transmit power	X		Fast effect
Radiation environment	X		Fast effect

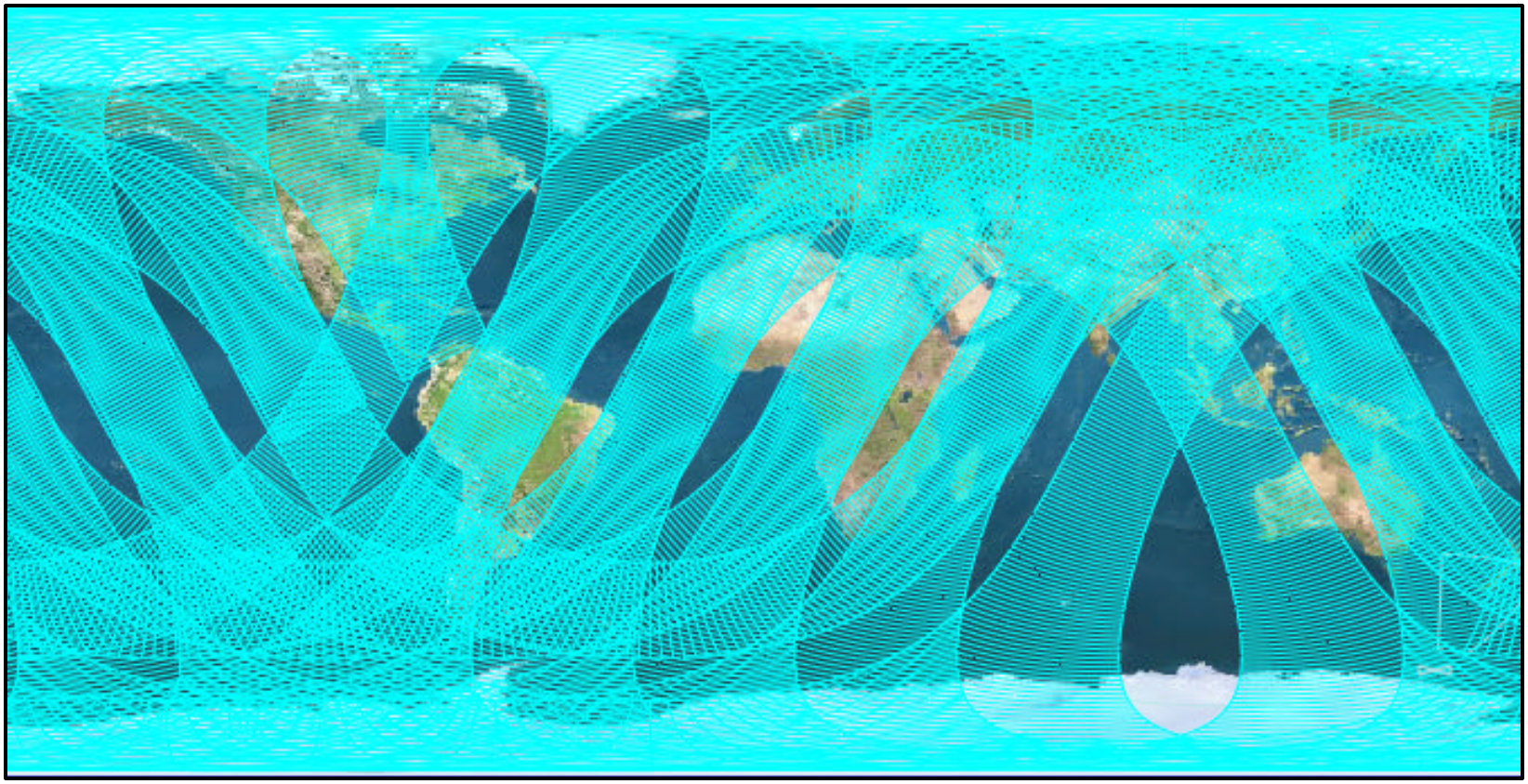
MEO Point Design

- Altitude 3040 km
  - Two-day repeat period (every 19 orbits)
  - Inclination 112° (sun-synchronous)
    - Dawn/dusk orbit gives better ionospheric conditions for InSAR
    - Simplified power and thermal subsystems
  - Coverage gaps typically ~12 hours, worst-case ~36 hours
  - Good 3-D displacement accuracy because of multiple look directions
  - Polarimetry possible for steeper incidence angles

- Antenna area 400 m^2 (10 x 40 m baselined)

3000 km MEO Accessibility

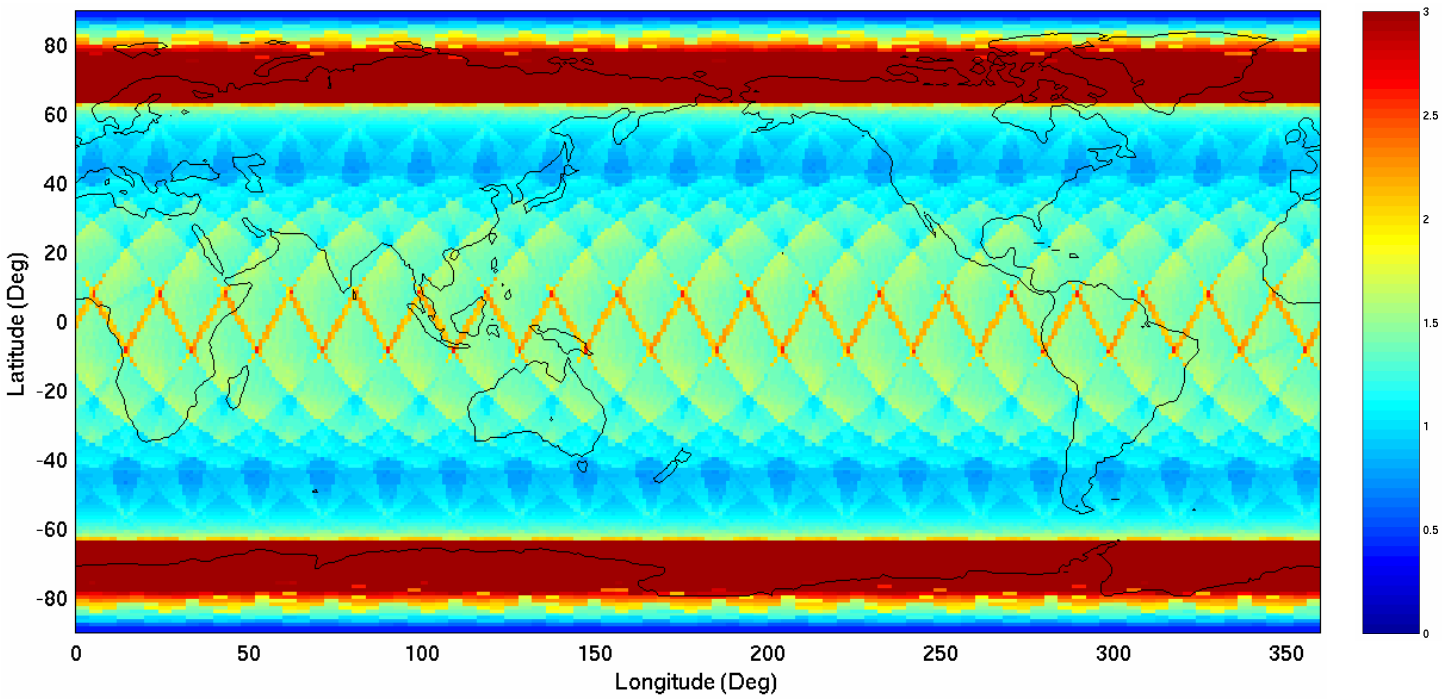
Nearly 90% of Earth surface accessible within 12 hours



Accessibility for a single SAR at 3000 km altitude after 12 hours

3-D Displacement Accuracy

- Resolving vector components of surface motion requires diversity of viewing angles for each ground location
- Very good 3-D accuracy achievable with MEO design



Worst vector component of 3-D displacement accuracy, normalized by line-of-sight accuracy, after incorporating all data from one repeat cycle

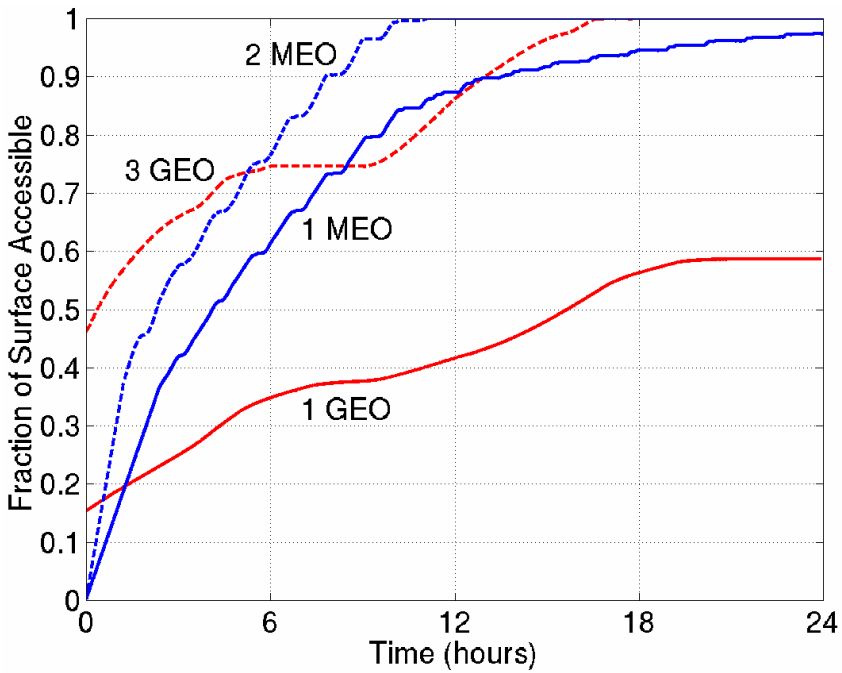
Radiation Effects

- MEO radiation environment is known to be severe
  - Total ionizing dose (TID)
  - Displacement damage
  - Charging/electrostatic discharge (ESD)
  - Single event upsets (SEU)
- Effects highly variable for different orbits
- Radiation especially of concern for lightweight-antenna technologies relying on distributed electronics–heavy shielding impossible
- Some radiation effects perhaps just as bad (or worse) at geosynchronous

Cumulative Accessibility

- Accessibility performance depends on requirements and time scales of interest

- Higher altitudes (e.g., geosynch, high MEO) perhaps better for time scales less than a few hours
- Lower altitudes (e.g., low MEO) perhaps better for time scales greater than a few hours



Shown: Cumulative percentage of Earth surface covered by various SAR configurations as a function of time. MEO altitude is 3040 km (2 day repeat for 1 platform, 1 day repeat for 2 platforms).

Conclusions

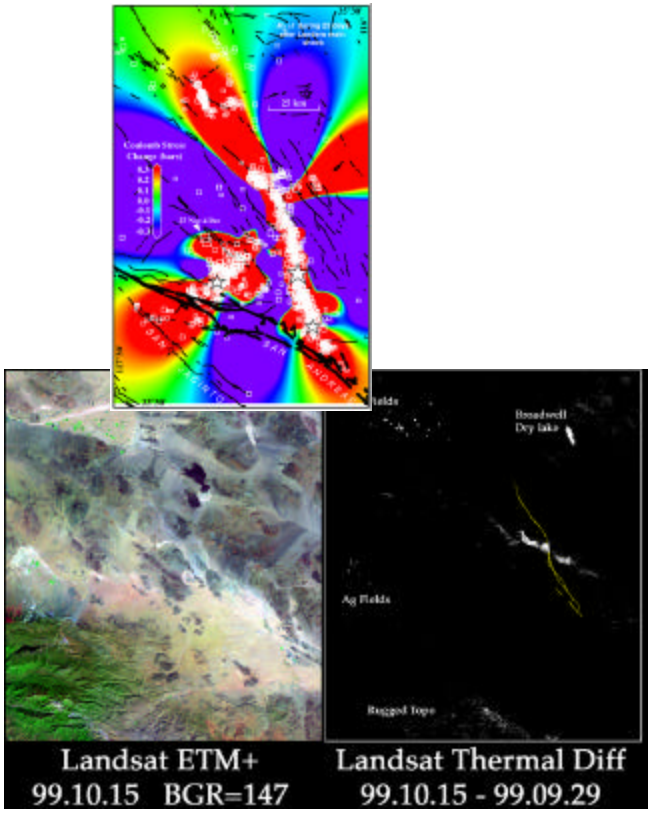
- High altitude vantage points (above 10,000 km) for SAR sensors could offer unique advantages in accessibility and operational flexibility
- Intermediate MEO altitudes (1500–5000 km) could offer significant advantages in reduced orbit repeat time and InSAR temporal sampling
- Development of lightweight antenna technologies needed for both

Backup Slides

Mapping Crustal Stress from Space

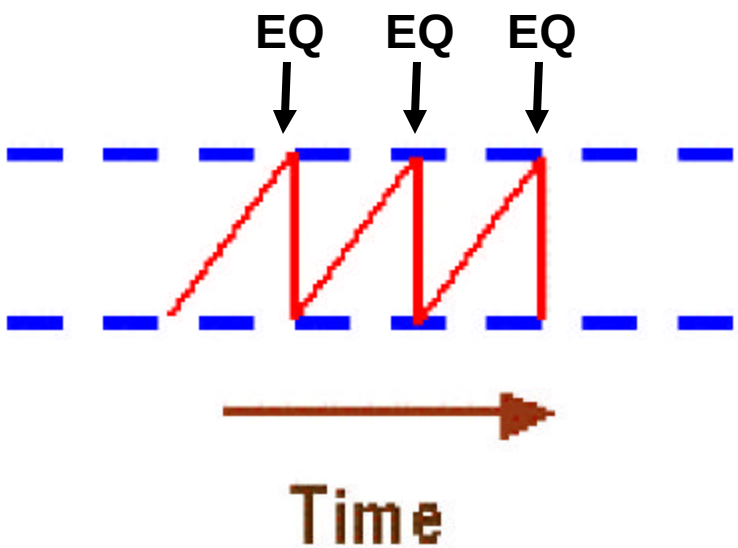
- Stress can be inferred from dense geodetic (InSAR and GPS) observations

- Thermal/IR and electromagnetic emissions may indicate the changing state of stress in the crust
  - VLF magnetic fields associated with earthquakes are thought to result from piezomagnetic effects
  - Thermal anomaly was observed for Hector Mine and possibly other earthquakes
  - However, no unequivocal systematic behavior has been identified, and physical explanations of observations are unsatisfactory or untested



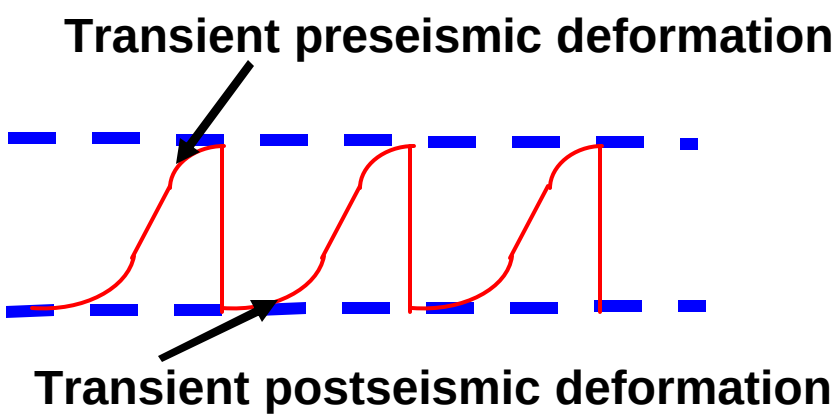
- We conclude that more systematic data analysis, and ground-based and laboratory research, into stress-related thermal and electromagnetic emissions is needed to define observational requirements
  - Addressed by ASTER, MODIS, Demeter (CNES), swarm(ESA)

The Earthquake Cycle



Simple Physics:

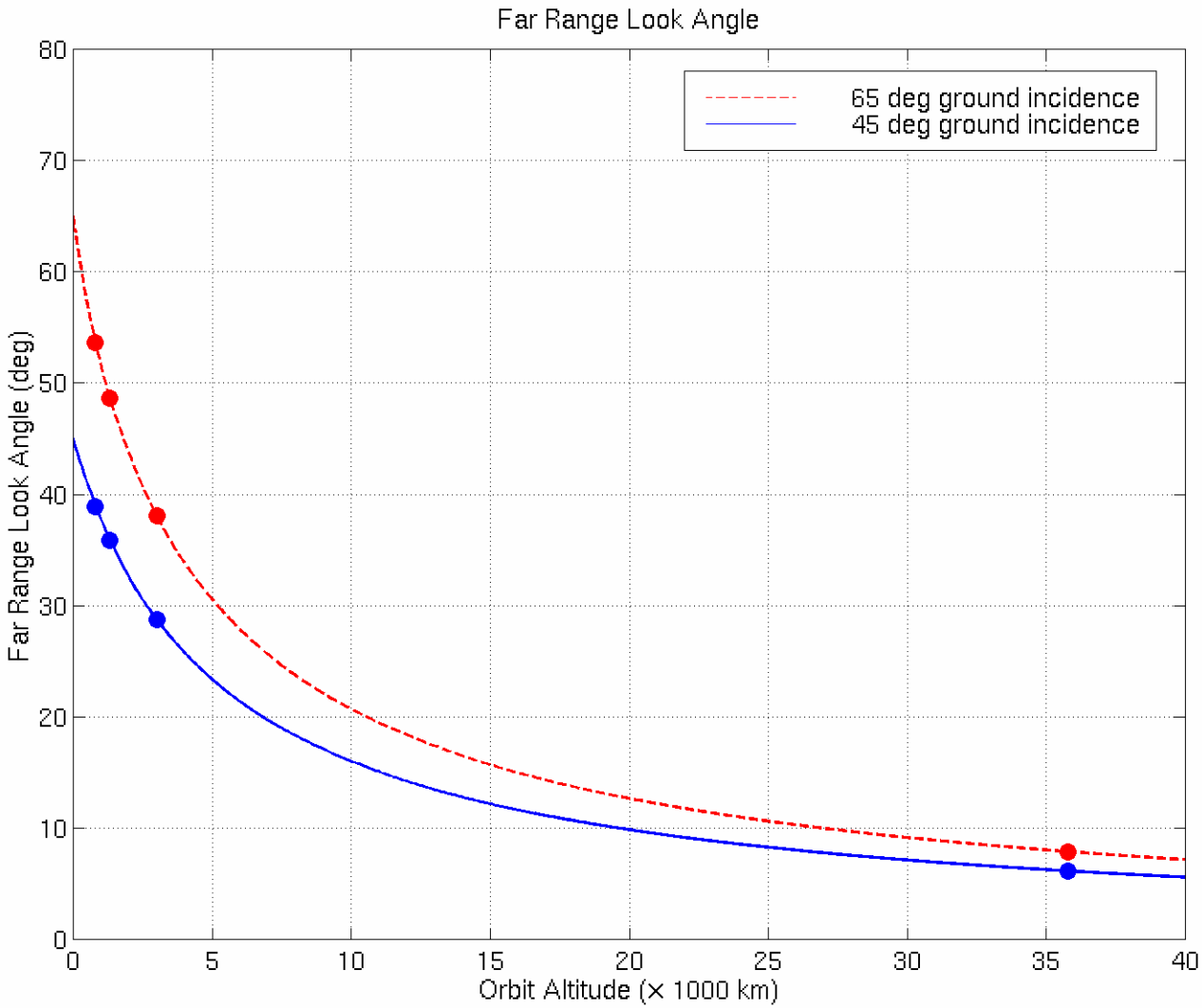
- **Surface Deformation linear**
- **Recurrence time is predictable**



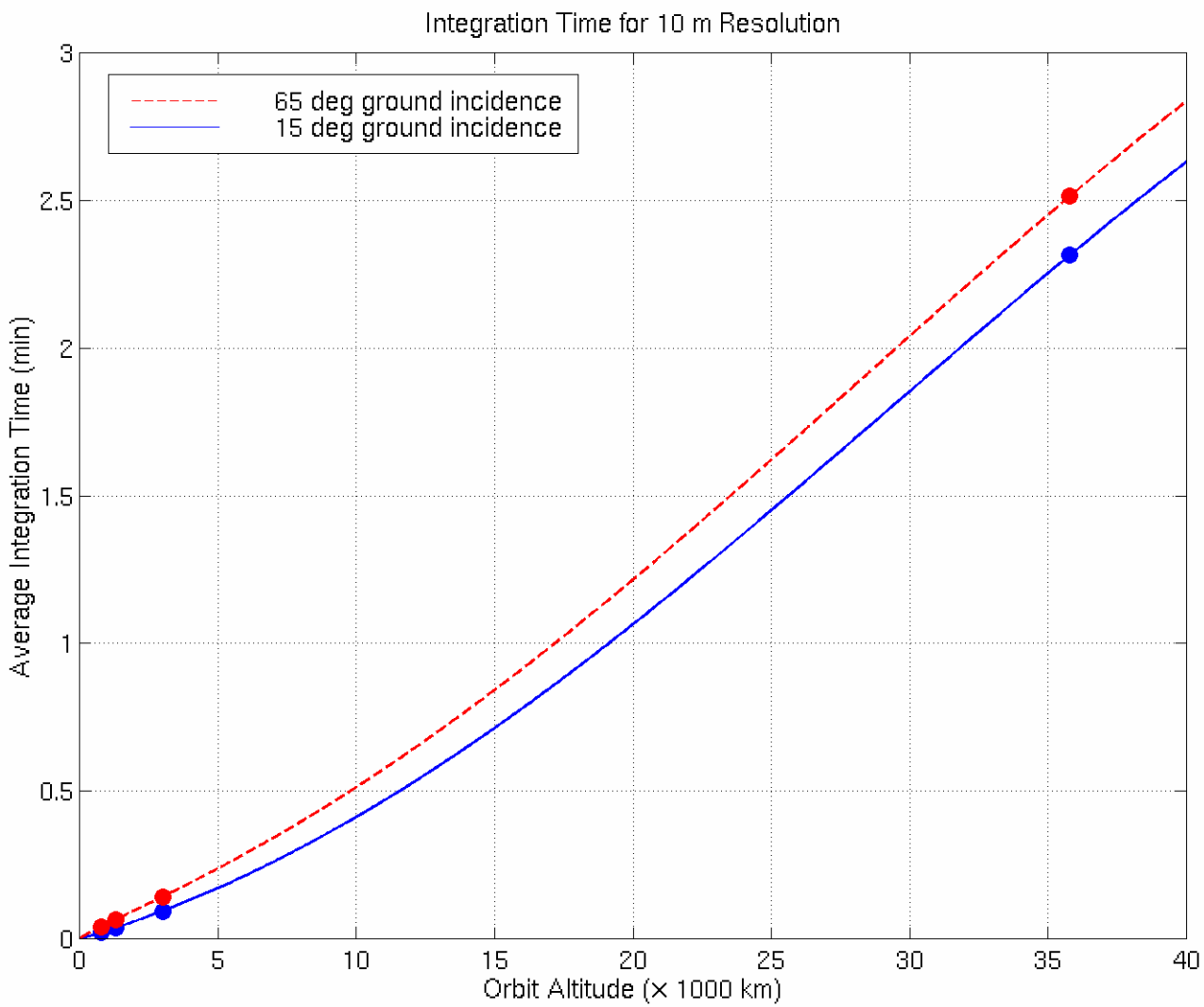
Complex Physics:

- **Surface Deformation non-linear**
- **Faults interact**

Far Range Look Angle vs. Altitude



SAR Integration Time vs. Altitude



Science/Mission Roadmap