Interferometric Imaging of Near Earth Asteroids

Astronomical Optics, Spring 2013

The Team

Ya-Lin Wu

Nate Wilkerson

Xiaoyin Zhu

Mike Butterfield

Outline

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- Astronomical Interferometry
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  - Existing and Planned Systems
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Goals

Assignment: AO Project 2: Interferometry: Asteroid surface mapping

- Asteroid mining company needs maps of asteroid surfaces
- Design an interferometer to map asteroid surfaces

What we were able to do:

- Define system requirements for meter-level resolution asteroid mapping for near-pass NEAs
  - Required defining the type of asteroid, maximum imaging range, and similar parameters
- Design an interferometric telescope array to meet those requirements
  - Discuss the spectral capabilities of the designed system
    - We were not able to easily relate the spectral capabilities of the system back to science
    - Instead, we say what we think we can do and describe where that becomes complicated

Science

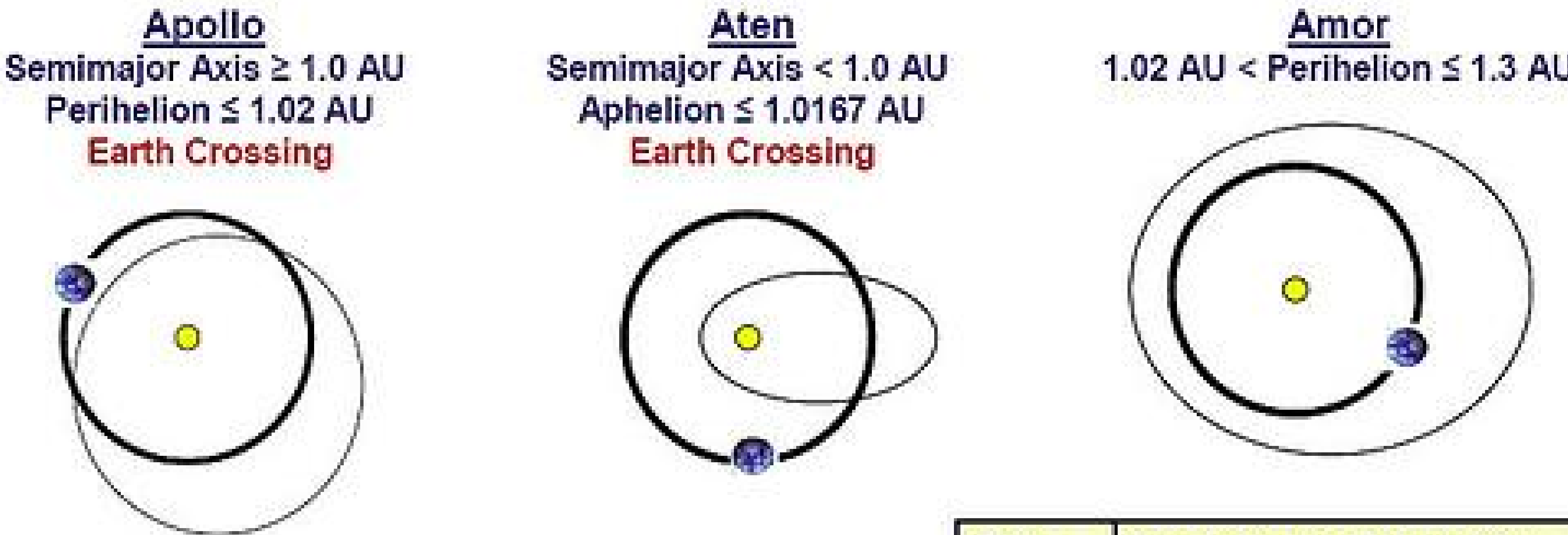
Astro-mining

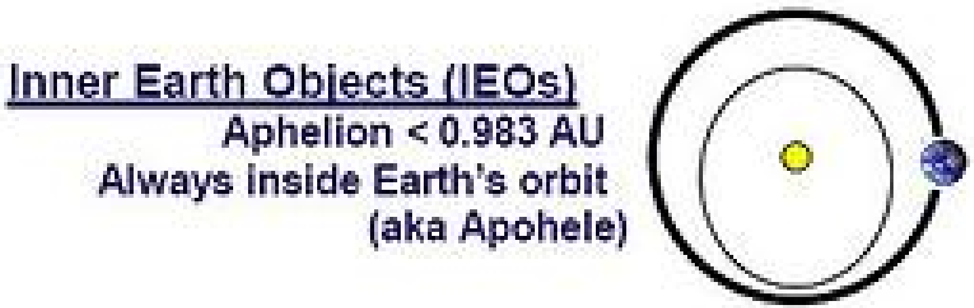
We love gold, iron, copper, silver, nickel, cobalt...
and we want to gain a lot of **profit**

NEOs are good targets

We have to map their surfaces in **meter-level** resolution
--> regions of interest, where to land ? overall shape...

We need an **interferometer**





Type	Near-Earth Population
Apollo	62% of known asteroids
Aten	6% of known asteroids
Amor	32% of known asteroids
IEO	6 known asteroids

Figure 1. Near Earth Asteroid Orbit Types

NEO Selection

Better imaging: they should be **large**

Meter-scale resolution: they should be **very close to us**

(10m @ 10LD --> 0.5 milli-arcsec in visible; a 500-m interferometer gives 0.2 milli-arcsec --> doable)

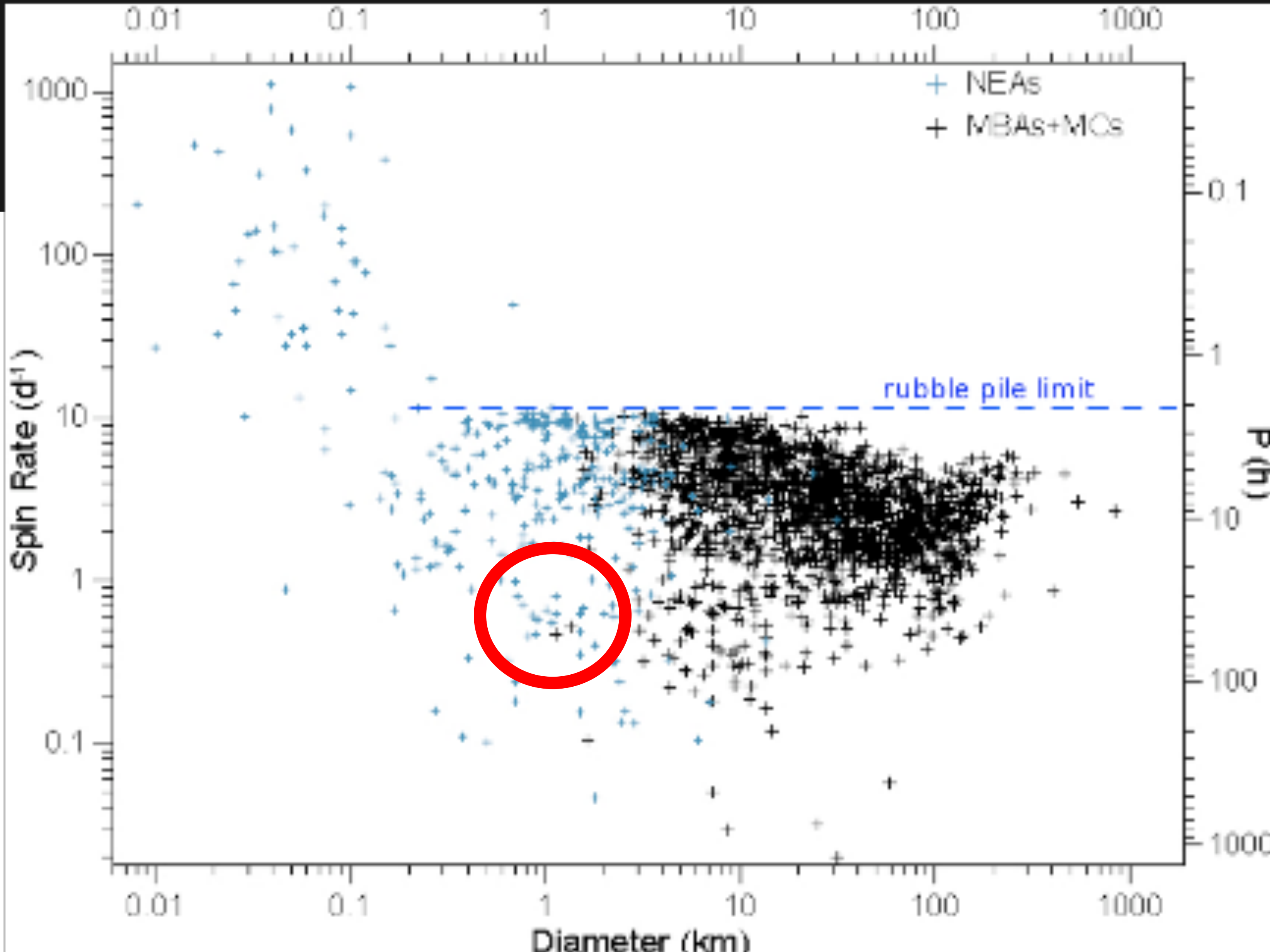
Less smearing in resolution: they should be **slow rotators**

(1km NEO with 50hr period --> rotates 1m in 60sec;

if v_rel=20 km/s, we have ~ 100 hr before they pass us --> at least 1 period available)

So we focus on 1 km, 10 LD, 50hr NEOs

--> they are not that rare



NEAs
MBAs+MCs
rubble pile limit
Spin Rate (d⁻¹)
P (h)
Diameter (km)
0.01
0.1
1
10
100
1000

Object Name	Close Approach Date	CA Distance* (AU)	CA Distance* (LD)	Estimated Diameter**	H (mag)	Relative Velocity (km/s)
163364 (2002 OD20)	2013-May-23	0.0388	15.1	470 m - 1.1 km	18.8	10.18
(2009 SB)	2013-May-23	0.1969	76.6	200 m - 460 m	20.6	31.78
172722 (2004 BV102)	2013-May-25	0.1795	69.9	840 m - 1.9 km	17.5	26.53
(2012 KF25)	2013-May-26	0.0793	30.9	23 m - 51 m	25.3	9.14
(2011 KE3)	2013-May-30	0.1303	50.7	43 m - 97 m	23.9	5.36
285263 (1998 QE2)	2013-May-31	0.0392	15.2	1.3 km - 3.0 km	16.5	10.58
(2011 BM45)	2013-Jun-01	0.0749	29.2	130 m - 280 m	21.6	27.67
(2004 KH17)	2013-Jun-03	0.0979	38.1	110 m - 250 m	21.9	12.91
152756 (1999 JV3)	2013-Jun-04	0.1425	55.5	450 m - 1000 m	18.9	13.64
152941 (2000 FM10)	2013-Jun-05	0.1293	50.3	790 m - 1.8 km	17.6	21.41
(2002 KL3)	2013-Jun-06	0.1706	66.4	690 m - 1.6 km	17.9	30.16
(2011 SD173)	2013-Jun-06	0.1925	74.9	330 m - 730 m	19.5	10.72
354182 (2002 DU3)	2013-Jun-09	0.1970	76.7	200 m - 450 m	20.6	6.21
53550 (2000 BF19)	2013-Jun-11	0.1655	64.4	430 m - 970 m	18.9	9.16
17188 (1999 WC2)	2013-Jun-12	0.1007	39.2	1.2 km - 2.6 km	16.8	20.38
(2011 OJ45)	2013-Jun-14	0.1992	77.5	18 m - 39 m	25.9	5.12
(2012 UL171)	2013-Jun-14	0.1878	73.1	10 m - 23 m	27.0	3.91
(2011 KR12)	2013-Jun-18	0.1670	65.0	140 m - 310 m	21.4	8.46
340666 (2006 RO36)	2013-Jun-18	0.1823	70.9	740 m - 1.7 km	17.8	12.76

S/N

For a 1km NEO, 1.7 W/m^2/nm irradiance, 10 LD, V band, 100nm bandwidth,10% albedo, 4-m aperture, we have 1.7 *pi*500^2*100/(3.6*10^(-19))*10%=3.7*10^25 ph/sec reflected from the NEO.

solid angle of telescope=2pi*(1/2*(2/4*10^9)^2)

# of photons/sec

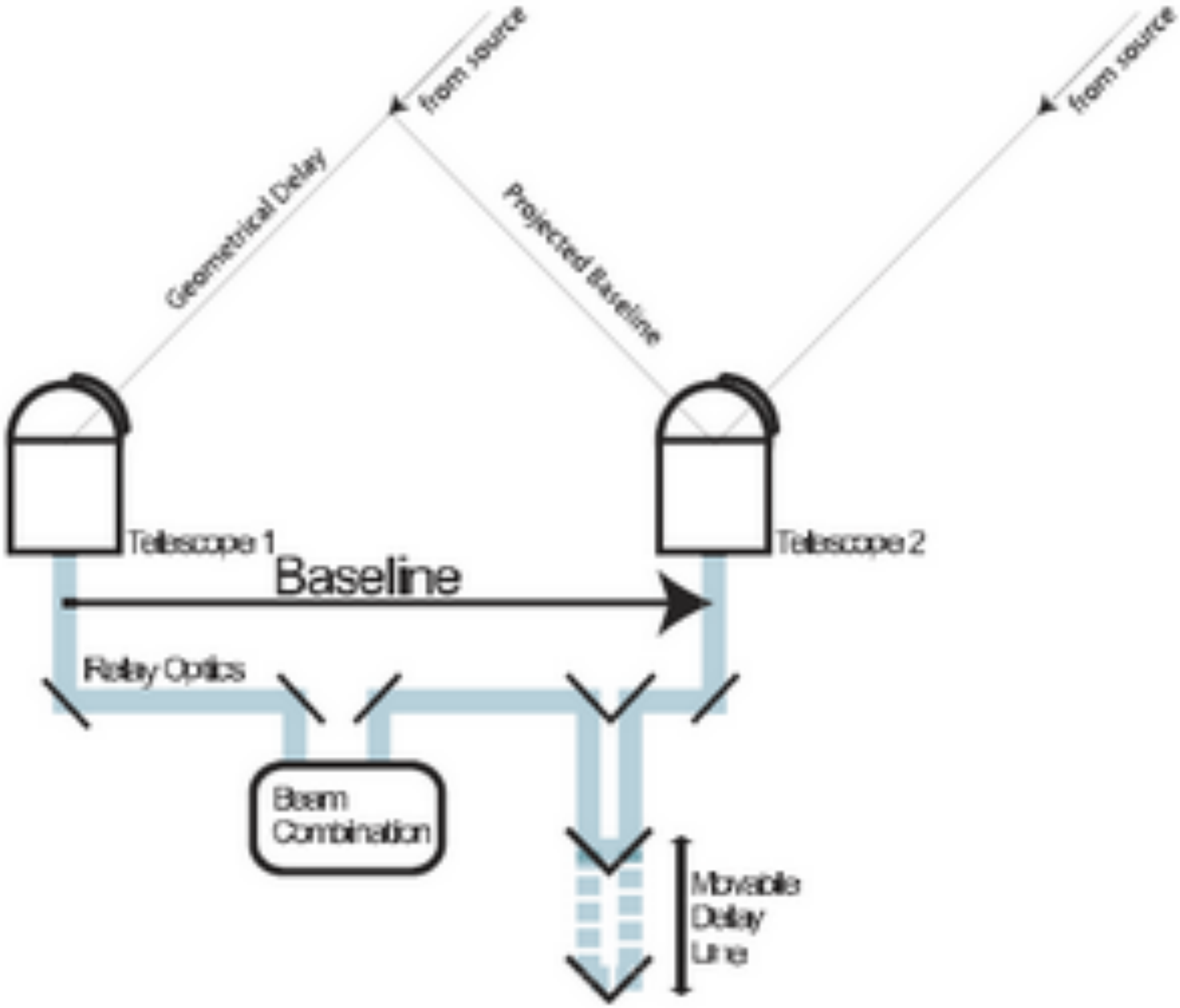
=3.7*10^25*2pi*(1/2*(2/4*10^9)^2)/2pi=4.6*10^6 or 11 mag.

(For 50 LD, 5nm bandwidth, we still have > 4000: good for spectroscopy)

Conclusion: we will have tons of photons & very high S/N!

Astronomical Interferometry

Astronomical Interferometer



major subsystems of a modern optical interferometer:

- telescopes
- relay optics
- delay lines
- beam combination

Astronomical Interferometry

Angular resolution. Diffraction limit of a telescope : λ/D (D: telescope diameter)
Diffraction limit of an interferometer: λ/B (B: baseline)

Visibility.

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{\text{Fringe amplitude}}{\text{Average intensity}}$$

Van Cittert-Zernike theorem gives the fringe Visibility as a function of baseline, λ, and stellar apparent size.

$$V^2(B\theta/\lambda) = \left(2\frac{J_1(\pi B\theta/\lambda)}{\pi B\theta/\lambda}\right)^2$$

Existing and Planned Systems

http://en.wikipedia.org/wiki/List_of_astronomical_interferometers_at_visible_and_infrared_wavelengths

Interferometer and observing mode	Waveband	Limiting magnitude	Minimum baseline (m) (un-projected)	Maximum baseline (m)	Approx. no. visibility measurements per year (measurements per night x nights used per year)	Max ratio of no. phase / no. amplitude measurements (measure of imaging performance, 0 = none)	Accuracy of amplitude[2] measurements	Accuracy of phase measurements (milli-radians)	Number of spectral channels (max in use simultaneously)
CHARA Array[1]	V, R, I, J, H, K	8	34	330	7500	0.7	1%	10	30000
COAST visible	R, I	7	4	60	2000	0.5	4%	10	4?
COAST infrared	J, H	3	4	60	100	0.5	20%	10	1
GI2T visible	R, I	5	10	65	2000	0	10%	-	400?
IOTA	J, H, K	7	6	30	10000	0.3	2%	10	1?
ISI	N	0	10	50	5000	0.3	1%	1	1000
Keck Interferometer	H, K, L, N	10.3	85	85	1000	0	4%	1	330

Interferometer and observing mode	Waveband	Limiting magnitude	Minimum baseline (m) (un-projected)	Maximum baseline (m)	Approx. no. visibility measurements per year (measurements per night x nights used per year)	Max ratio of no. phase / no. amplitude measurements (measure of imaging performance, 0 = none)
LBTI (near infrared)	J, H, K	>20	0	22	10000000	1
MRO	R, I, J, H, K	14	7	400	100000	0.6
VLTI (near infrared using 4 ATs and PRIMA)	J, H, K	12	8	200	10000	1
VLTI (near infrared using 3 UTs and PRIMA)	J, H, K	14	46	130	500	1

Existing and Planned Systems

Acronym	Telescope Number	Telescope Size (m)	Maximum baseline (m)	Wavelength coverage
CHARA	6∗	1.0	330	Visible∗, near-IR
COAST	5	0.40	47 (100∗)	Visible and near-IR
GI2T	2	1.52	65	Visible, near-IR
IOTA	3	0.45	38	Visible, near-IR, 4 μm
ISI	3∗	1.65	85 (>100∗)	Mid-IR
Keck-I	2	10.0	85	Near-IR, mid-IR∗
MIRA-I	2	0.25	30	Visible
NPOI	6	0.12	64 (>250∗)	Visible
PTI	3	0.40	110	Near-IR
SUSI	2	0.14	64 (640∗)	Visible
VLTI-UT	4	8.0	130	Near-IR, mid-IR
Keck∗	4∗	1.8	140∗	Near-IR
LBTI∗	2∗	8.4	23∗	Near-IR, mid-IR
MRO∗	~10	~1.5	~1000	Visible, near-IR
OHANA∗	~6	3.5–10	~1000	Near-IR
VLTI-AT∗	3∗	1.8	202	Near-IR, mid-IR

CHARA

Y-shaped Array Configuration

- 15 baselines from 31 to 331 meters
- World’s longest operational IR baseline

Six 1.0-meter Collecting Telescopes

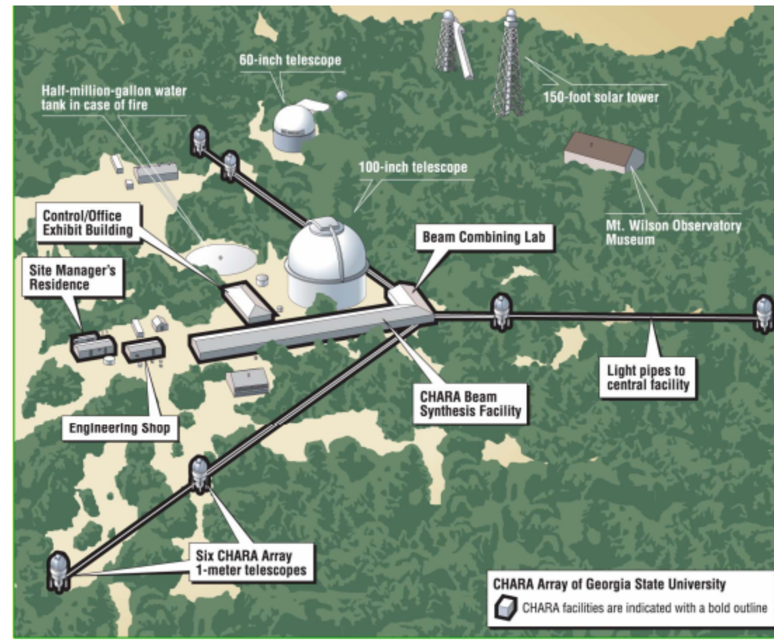
- Can accommodate 2 more telescopes
- AO retrofit currently being explored

Dual Operating Wavelength Regimes

- 470 - 800 nm (0.15 mas limiting resolution)
- 2.0 - 2.5 microns (0.6 mas limiting resolution)

Science Emphasis on Fundamental Stellar Parameters

- Sizes, shapes, distances, temperatures, masses & luminosities



Current Generation: LBT

The Large Binocular Telescope Interferometer is a system which includes "nulling interferometry" or a nulling mode - which will directly image planets in other solar systems. It leverages this setup to deliver 23 m resolution capabilities. The system is optimized for observations in the thermal infrared.

These capabilites are being developed to explore the nature of nearby exoplanetary systems. These observations will improve our understanding of asteroid belts and giant planters around nearby stars, an important stepping stone toward future direct imaging of Earth-like planets.

Keck

Keck Interferometer (KI) uses the world's largest pair of optical telescopes, the Keck Telescopes, to create an interferometer with a sensitivity unmatched by any ground-based instrument of its type.

Using a nulling technique, KI is being used to directly observe dust known as zodiacal dust around nearby stars to provide information about planet formation, and to help plan how to reduce noise from exozodiacal dust for future missions.As of end of semester 2012A, the Keck Interferometer is no longer operational.

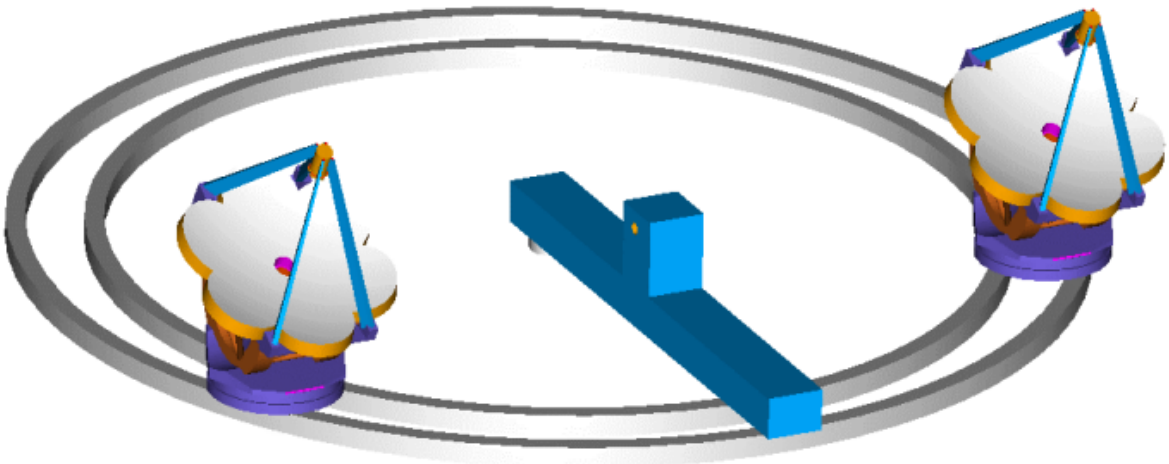
Keck Interferometer with fixed 85 m spacing

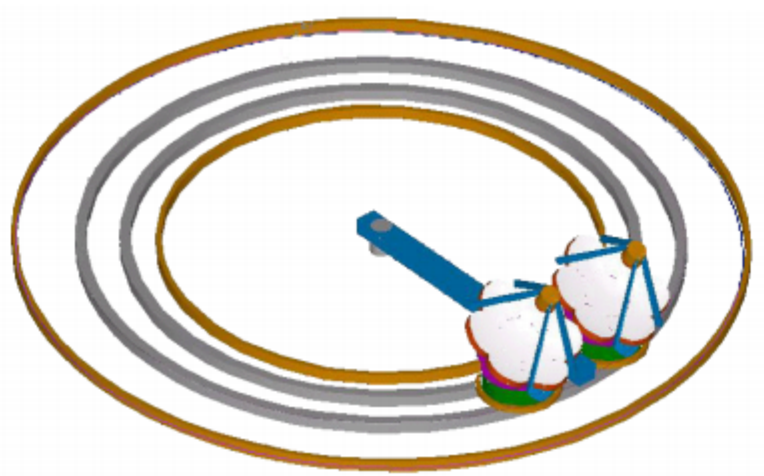
VLTI

The Very Large Telescope Interferometer (VLTI) consists in the coherent combination of the four VLT Unit Telescopes and of the four moveable 1.8m Auxiliary Telescopes. Once fully operational, the VLTI will provide both a high sensitivity as well as milli-arcsec angular resolution using baselines of up to 200m length.

Next-generation: 20/20 Telescope

The cryogenic beam-combiner moves in sync. with the two telescopes, holding a position midway between. We show it in brown mounted on a 50 m radial beam, shown in blue.





The telescope enclosures could be moved on a separate track (brown) or they could remain fixed with the telescopes operating in the open or with separately driven wind shields.

Proposed Space Interferometers

Acronym	Full name and primary science drivers
SIM (NASA)	Space Interferometry Mission Precision astrometry; exosolar planets
FKSI (NASA)	Fourier–Kelvin Space Interferometer Find Jovian planets (nuller); map circumstellar discs
SMART-3 (ESA)	SMART-3 Test free-flying concept for ESA IRSI-Darwin mission
IRSI-Darwin (ESA)	Infra-Red Space Interferometer (one concept: Darwin) Image terrestrial planets (IR nuller); measure spectra
TPF (NASA)	Terrestrial Planet Finder Image terrestrial planets (IR nuller); measure spectra
SPIRIT (NASA)	Space Infrared Interferometry Trailblazer Far-IR, sub-mm galaxy counts; precurser to SPECS
SPECS (NASA)	Submillimetre Probe of the Evolution of Cosmic Structure High-resolution map of high-Z universe (far-IR, sub-mm)
SI (NASA)	Stellar Imager Image surfaces of stars (visible, ultraviolet)
MAXIM (NASA)	Micro-Arcsecond X-ray Imaging Mission Map black hole accretion discs and event horizons (x-rays)
MAXIM Pathfinder (NASA)	MAXIM Pathfinder Demonstrate feasibility of x-ray interferometry; achieve 100 μ-arcsecond resolution
LF (NASA)	Life Finder Search for biomarkers in planet spectra; TPF extension
PI (NASA)	Planet Imager Image surfaces of terrestrial planets, 25×25 pixels (requires 6000 km baselines, futuristic!)

System Engineering

System Engineering

- Largest Telescope Capabilities:
  - For wavelengths of 1 micron, a 10 m aperture diameter telescope can perform 1m imaging at ranges out to ~0.00007 AU (10^4 km)
    - Mean Lunar distance is 384,400 km (0.00256 AU)
- Interferometers can provide effective apertures >100 m
  - 1 m surface imaging at AU is possible with a 100 m aperture (10^5 km)
  - For 1m imaging of objects at 1 Lunar distance, a 192 m baseline interferometer is required (lambda = 500 nm)
- Latest close approach in the news came inside the GEO belt
  - Survey showed 10 to 100 LD approaches are regularly available
  - Baseline needs to be large enough to provide useful information on these approaches
  - Baseline grows linearly with range, so

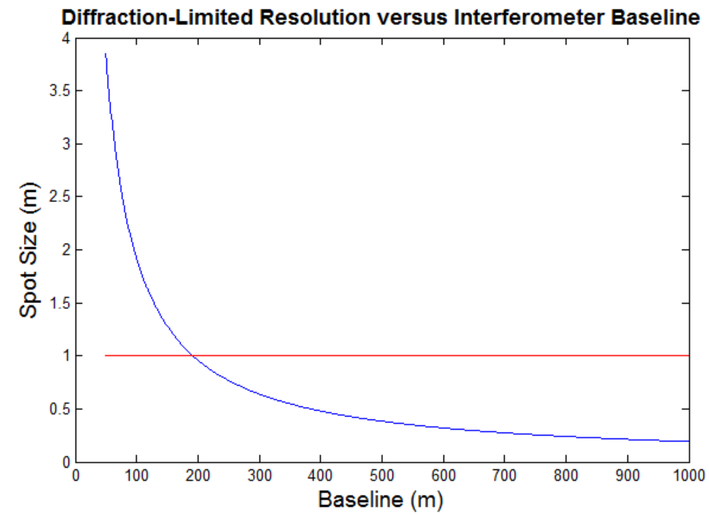
Reiterating the Target Asteroid Parameters

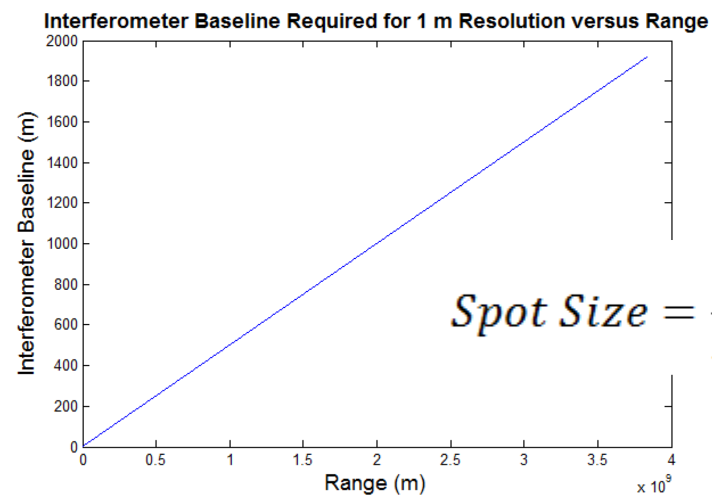
- Orbital restriction - 2-4 nights of good viewing an object
  - Restriction to 4 nights of measurements
  - Means that we get to do each phase measurement once rather than multiple times
- Rotation restrictions
  - Must be roatinging along a conducive axis
  - Must be a slow rotator ~ 24 to 72 hours
    - Provides good imaging of the portions of the asteroid that are visible from the observatory during those nights
      - ~6-8 hours of good measurements per night for 4 nights
      - Mapping of ~ 24 hours of the orbit is possible
      - Some regions are not mapped
        - Likely those areas near the rotation poles
        - Areas that are not exposed

Interferometer Design

Meter-level resolution is the requirement but the question is open ended

- At what range?
  - Our answer is the maximum physically possible range
- The spot size increases with range
  - At 1 lunar distance, a ~200 m baseline is required for 1 m resolution at 500 nm wavelength
  - For a fixed spot size of 1 m, the required baseline increases linearly
  - At 10 lunar distances the requirement is a 2 km baseline
    - Probably too large to be realistic
    - 1 LD = 0.26% of an AU
- What wavelength and ground or space-based?
  - IR is easier but the signal for NEOs in close approaches is higher from reflected sunlight
  - Space-based would work but this problem can be accomplished with reasonable systems on the ground





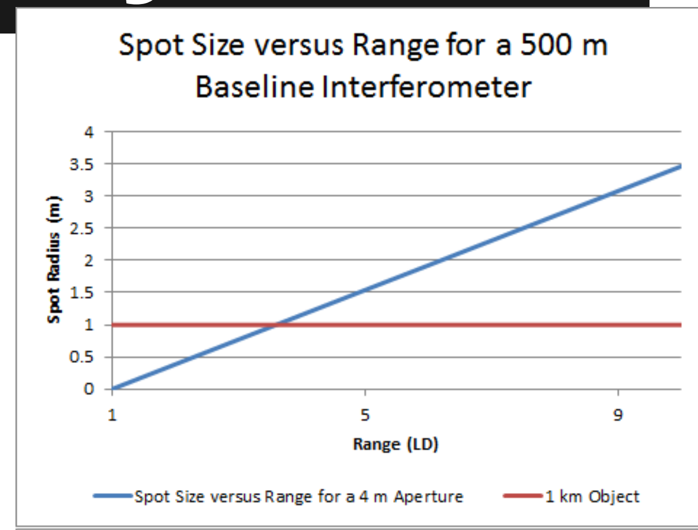
$$Spot\ Size = \frac{\lambda}{D} R$$

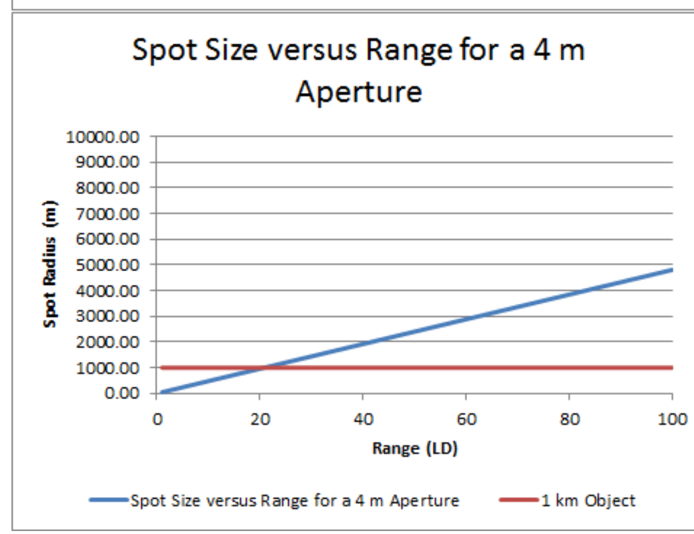
Final Baseline Selection

- Need to select a realistic baseline
  - What is a reasonable baseline?
    - Larger baselines bring higher resolution while increasing
      - Cost
      - Total measurement time
        - To fill in the uv plane
      - System complexity
    - In addition, visibility decreases with baseline, requiring larger telescopes
  - Existing and proposed long-baseline optical interferometers
    - Existing: CHARA: 330 m
    - Existing: COAST 60 m
    - Existing: Keck has an 85 m fixed baseline
    - Proposed: Magdalena Ridge Optical Interferometer would be 400 m if constructed
    - Proposed: 20/20 telescope would be 100 m
- Using a similar design to the 20/20 telescope with smaller apertures and a longer baseline could provide the required resolution and meet the visibility requirements
  - Lets choose a 500 m baseline
    - Projected baseline is ~350 m at a 45 degree angle

500 m Baseline Interferometer Analysis

- We looked at how well this system will perform versus range
  - If we can control the noise sources that reduce visibility, we will have <1 m resolution out to a maximum range of ~2.6 LD
    - Less for projected baselines
  - The object will be "resolved" for the 4 m telescope out to ~20 LD
  - Useful at 26 LD for 10 m resolution
  - Still useful at 100 LD (~.25 AU) - provides 38.4 m resolution!
- The system will provide the desired performance for our target asteroid size, orbit, and rotation rate





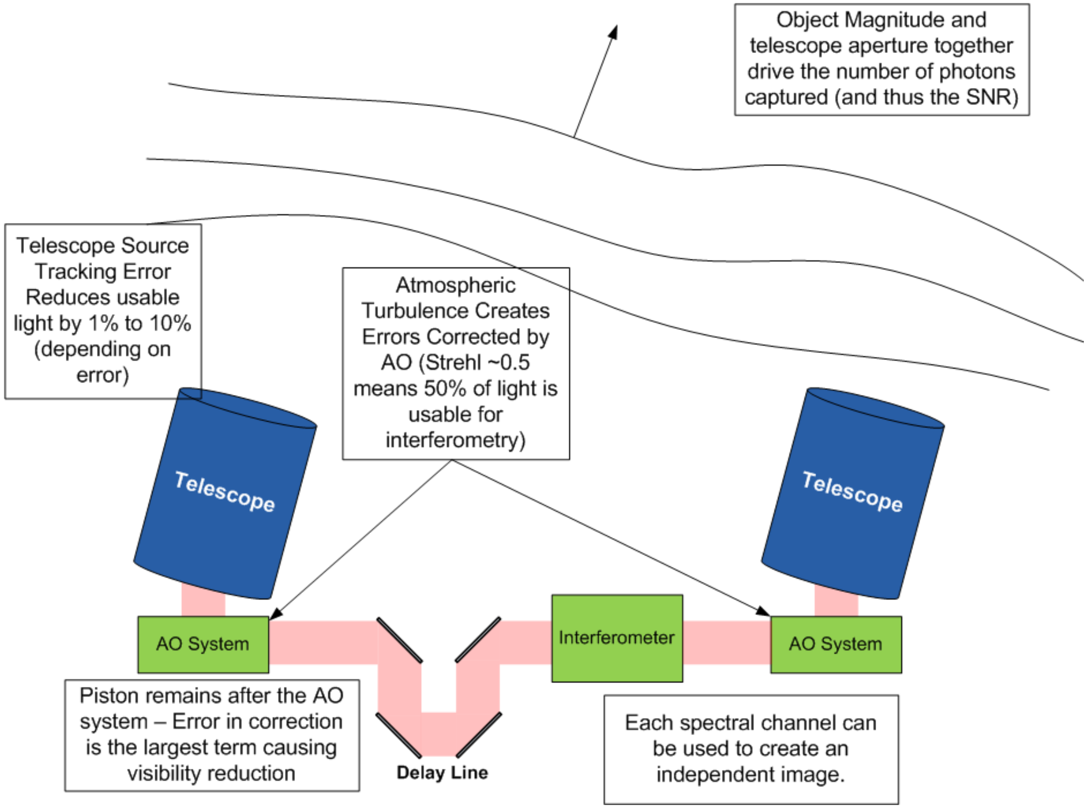
Design Overview

What can we offer with this system?

- 1000 m object at 10 LU
  - 4 meter aperture provides 481 m DL spot at asteroid
  - Albedo of 0.1 assumed
- Spectrometers provide images in 5 nm spectral bands
  - 600 nm bandwidth, 120 pixel linear sensor, resolution = 5nm
- Assume great detectors (80% QE) and fair optic and atmospheric transmission (~80% optics * 80% atm = 64% net)
  - Adaptive optics system is required
  - 4 m aperture, r0 ~0.1, needs 1600 actuators
- 12 Telescopes in an array
  - Light is effectively split 11 * 120 = 1650 ways
  - Object is 11th magnitude
  - SNR per band for this configuration is very high (SNR > 100)

Visibility Reduction: Noise Sources

- Source Motion
  - Rotation and Orbit
  - Mitigation: Short (relatively) integration time
- Atmosphere
  - Mitigated by AO
  - Piston Remains
    1. Random for every telescope
- Tracking and Pointing
  - Must be << diffraction limit
    1. DL = 2.50e-7 radians
    2. << DL is ~2 nanoradians
  - Requires fast steering mirror
    1. Probably operating at 1kHz
- System vibrations (jitter), thermal material expansion, and similar noise sources must be controlled
  - Handled through mechanical design

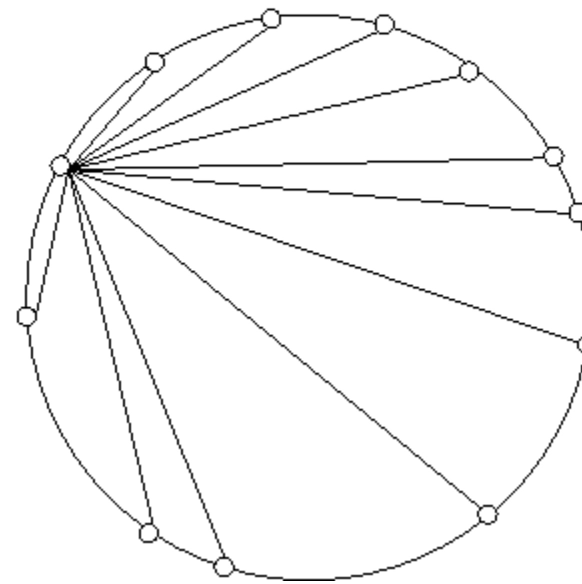


Sampling Configuration

- Configuration: 20/20-style circular track, 500 m in diameter
  - Ten 4 meter aperture telescopes
    - On tracks (think a circular railroad)
    - Potentially tracks objects by moving on the tracks (keeping baseline fixed to the sky)
      - Provides long integration times if required
  - Centrally located interferometer station
    - Contains 9 interferometers
    - Contains optical switches
- Metrology, Telescope Pointing, and Telescope Tracking
  - Need to know the positions of the telescopes very accurately
    - Path length differences must be controlled to << 1 wavelength for interferometry
    - Can be performed on the optical system
      - Laser projected through the system
    - Once known, piston is the largest issue
- Light from the telescope is sent to the to the center of the ring
  - Split into 11 independent interferometers (each telescope signal is interfered with all 1 other telescope's signals)
  - Phase closure required to eliminate piston

Baseline Sampling Explanation

- Connect lines between all of the telescopes that make up the system
  - Each line represents a baseline that can be controlled by changing the position of the telescopes along the circle
  - Any baseline <=500 m can be achieved (within mechanical constraints!)
- This design provides for fast uv plane sampling



(Above: Example baselines achieved for one telescope's connections to 11 others.

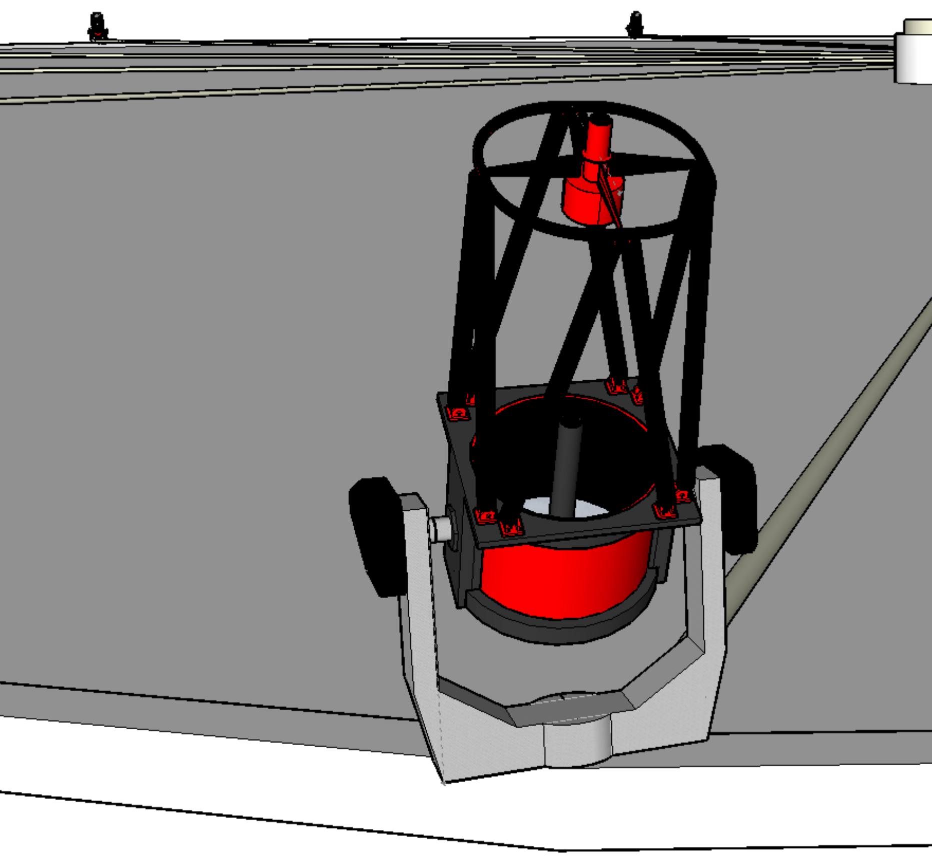
How is this operated? Multiple Configurations

- To build up a properly ,but non-redundantly, sampled aperture, multiple configurations are required in order to sample with all required baselines
  - Hundreds of total configurations are estimated to be required (did not have a great way to estimate this!)
    - 66 baselines are created for the 11-way split for each position
      - Say we use 6 configurations
      - 1 configuration takes < 30 s to integrate (4 sampled interferometer positions) and a minute (or so) to move and reconfigure (likely longer, but we can try)
      - Goal for a full image data capture (of one portion of the asteroid) could be as little as 10 minutes (
  - Post-processing creates the image from the measured data
- Current unknown: not sure how many samples are required
  - Need better understanding of uv plane sampling requirements

Optical and Mechanical

Optical & Mechanical Design

RC Telescope x12 on two axis gimbal and tracks

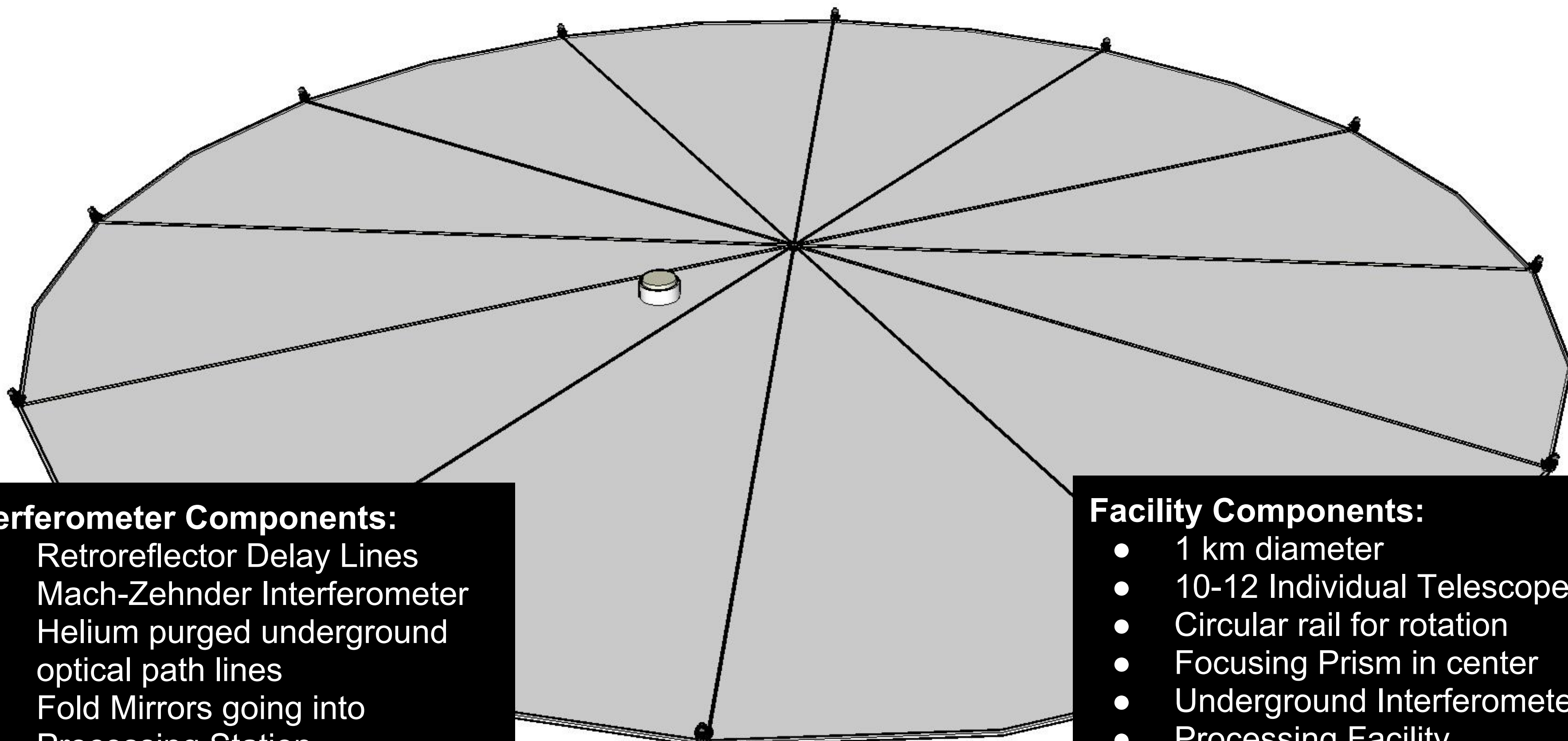


Optical Prescriptions:

- 4 meter aperture
- F/6.8 Ritchey Chretien design
    - All-reflective, works for all wavelengths (that the coating reflects)
- Fast-steering mirror provides rapid tracking corrections
- Error reduced to 2 nm per cm after AO Systems
- 0 to 180 deg. Elevation Range
- 0 to 360 deg. Azimuthal Range

Top View of Facility

Non-Redundant Sparse-Aperture

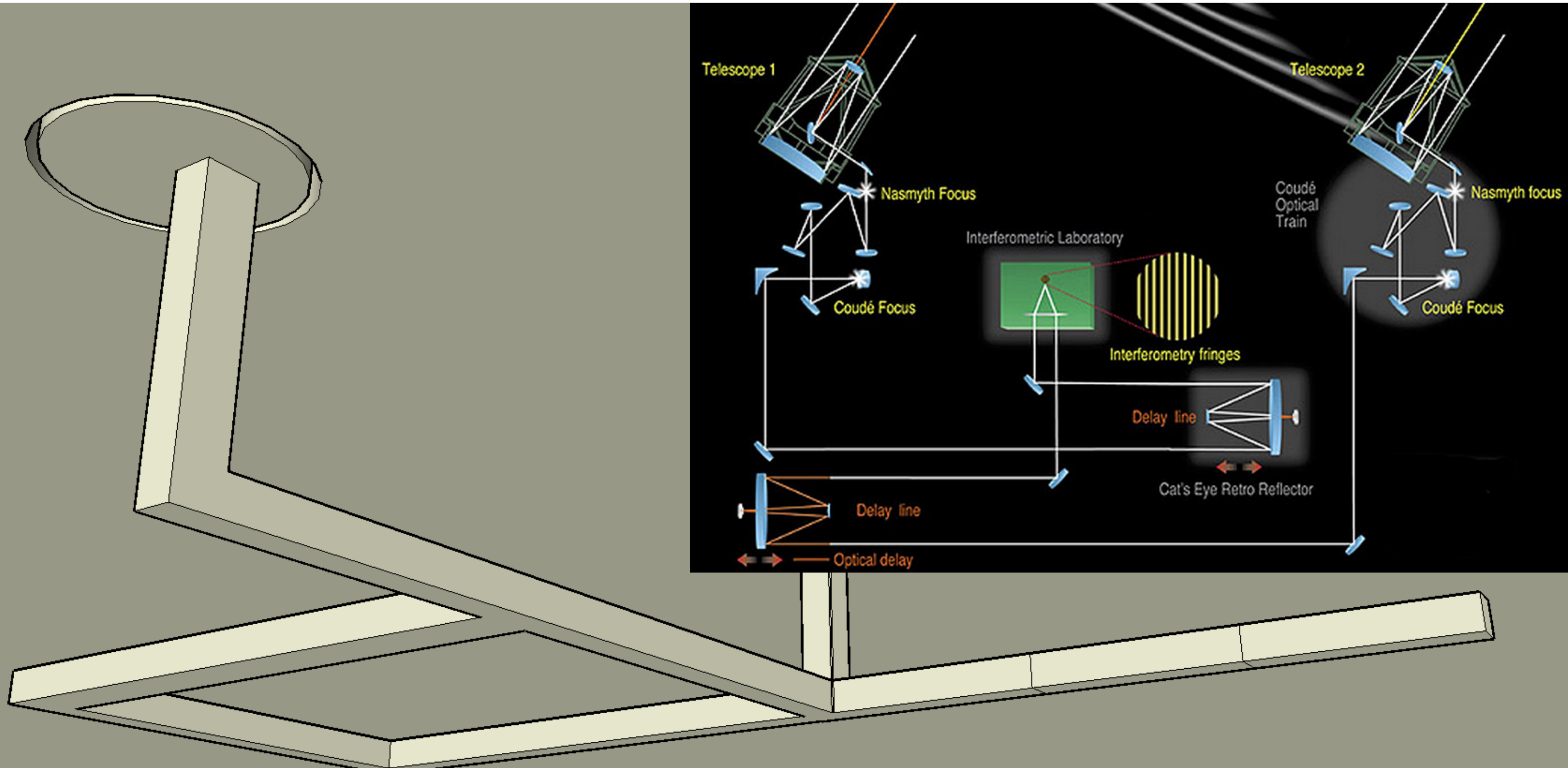


Interferometer Components:
- Retroreflector Delay Lines
- Mach-Zehnder Interferometer
- Helium purged underground optical path lines
- Fold Mirrors going into Processing Station

Facility Components:
- 1 km diameter
- 10-12 Individual Telescopes
- Circular rail for rotation
- Focusing Prism in center
- Underground Interferometer
- Processing Facility

Underground Interferometer

Mach-Zehnder with Cat's Eye Delay Line



VLT Interferometer
http://www.millhouse.nl/vlt001.html