# A Survey of Conventional and Unconventional Methods for Imaging GEOS with Ground Based Interferometers and Large Aperture Telescopes

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*Abstract*— **This paper presents a survey conventional and unconventional methods for imaging objects in space, specifically GEOS. The goal is to gather in one place details regarding existing facilities and methodologies so as to be able to better appreciate the capabilities – strengths, weakness, and appropriateness – of each.**

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## 1. INTRODUCTION

GEO satellites which orbit the earth at about 22,400 miles make up an important class of man-made objects in space; most of our commercial and military communication satellites reside in this orbit. There are many ongoing programs to develop a high-resolution, ground-based imaging capability, utilizing both active and passive techniques to image these GEO objects. Despite the work no system yet has been able to adequately provide the high (~5-10cm) resolution that is required. Imaging at this level requires very large collection apertures. In addition large collection apertures are needed since many of the objects have visual magnitudes Mv = 12 or fainter. In the last decade many large telescope facilities have been built for astronomical applications but have not been adequately designed as imagers for LEO or GEO applications. Building new facilities for this would be very expensive. We present two approaches, 1) applying new and novel imaging methods to existing large aperture telescopes and 2) new unconventional imaging methods that do not require large expensive new telescopes

## 2. GROUND BASED IMAGING THROUGH TURBULENCE

The biggest complication to imaging extended objects in space, those whose angular extent is larger than the isoplanatic angle, like satellites in LEO, is turbulence. Light reflected off an object (passive solar or active laser illumination) contains information about the object.

The atmosphere degrades an image by convolving the irradiance distribution of the object with the term that includes both the atmosphere and the telescope. In Fourier space this simplifies to [1]

$$\langle I(u)\rangle = O(u)\cdot\langle S(u)\rangle \qquad (1)$$

where u is the spatial frequency, $\langle I(u)\rangle$ is the time averaged measurement, $O(u)$ is the object, and $\langle S(u)\rangle$ is the time averaged optical transfer function for the telescope and atmosphere, which for long exposures is given by

$$\langle S(u)\rangle = T(u)\cdot B(u) \qquad (2)$$

where $T(u)$ is the telescope transfer function and $B(u)$ is the atmospheric transfer function. Fried showed that the resolving power R of a telescope is related to $\langle S(u)\rangle$ by

$$R = \int\langle S(u)\rangle du = \int T(u)\cdot B(u)du \qquad (3)$$

Fried defined a parameter r0 which is the critical diameter of the telescope. It is defined as the point at which the atmospheric coherence function equals the telescope transfer function,

$$\int B(u)du = \int T(u)du \qquad (4)$$

and the resolving power of the telescope is limited by the size of the optics as long as D<r0. When D>r0 the $B(u)$ term dominates and resolution is no longer $\lambda$/D but now $\lambda$/r0. This can be fixed through the use of various techniques or through the use of adaptive optics both of which will be which will be discussed below.

The relationship between the atmospheric coherence function and r0 is given by [2]

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$$B(u) = \exp\{-3.44(\lambda u/r0)^{-5/3} \quad (5)$$

## 3. CONVENTIONAL IMAGING METHODS

*Refracting Telescope*

The simplest conventional imaging device that could be utilized for imaging GEO satellites is a refracting telescope consisting of a pair of convex lenses; a light capturing lens and an eyepiece lens. The magnification is then the ratio of the focal lengths of these two. This is sufficient when very high magnification is not required or the distance to the object being viewed is not very far. For astronomical imaging where the distances are quite large, the size of the telescope requires very large optics which costly and cumbersome. In fact with the new class of the telescopes like the Keck, the f/# of the primary needs to be as short as possible to keep the size of the support structure manageable. We will discuss in the following section, various imaging methods that can be applied on existing telescopes and new methods that do not require expensive infrastructure.

*Single-Aperture Telescope*

Optical telescopes provide two functions, 1) they collect light form the object being imaging and 2) provide resolving power to see small details on the object. The light collection capability comes from the size of the collection aperture or entrance pupil of the telescope. Larger apertures collect more light. Resolving power, on the other hand, is a little more complicated. Increasing the aperture size also allows for resolving smaller detail however, as noted above, atmospheric turbulence limits the effective aperture size for resolving detail. The limit on aperture size for resolving power is r0, or the Fried parameter. This parameter is essentially the size of the coherent length in the atmosphere, i.e. rays from the object that must transverse through the atmosphere. If they pass through different r0 patches then they will no longer be coherent. This r0 parameter is dependent on the wavelength which can complicate multi spectral imaging. Typical astronomical sites have r0 in the 10-20 cm range for visible wavelengths [3]. Therefore a telescope with a 1m aperture at a site with 10 cm r0, will resolve an object no better than a telescope with a 10 cm aperture. The larger telescope will of course collect more light and therefore ‘see’ dimmer object but the resolution is limited by r0. Adaptive optics can be used to correct the atmospheric turbulence. A wavefront sensor, for example a Shack-Hartman detector, monitors a star in real time and measures the rapid displacement caused by the turbulence. This information is then fed in real time to a deformable mirror which then makes small displacements of the individual surface segments to counter the atmospheric displacement, thereby cancelling them out. An important point to consider is that as the size of these telescopes gets larger (and D/r0 increases) the turbulence gets harder to correct and the costs of the system gets prohibitively large. Nevertheless, progress has been made and The US Air Force AEOS telescope on Maui and the SST telescope, now operated by The Massachusetts Institute of Technology's Lincoln Laboratory, are in particular dedicated, amongst other projects, to the developing the capability of imaging satellites.

*Interferometric Array*

The next class of imaging devices uses an array of small telescopes with an interferometric method. The use of an array of smaller telescopes helps keep costs lower and the interferometric method allows it to image with a sparse array, i.e., the array does not have to have an aperture for every potential Fourier component. Its drawback is the stability and path matching required to form fringes between the pairs of apertures. The image is formed through post processing where the interfering signal from the individual apertures each represent the signal for one component in the Fourier plane. The collection of these Fourier components allows the image to be reconstructed.

In order for a pair of small apertures to be combined (interfered) to form the complex visibility and hence provide one point in the uv plane, their signals have to be coherent with respect to one another which means that the paths to the detector have to be carefully matched.

In addition, the process requires a complex optical path. Since the targets are initially very faint, reflecting surfaces in the optical train only results in more optical loss, e.g., even with reflective optics that have reflection coefficients of 0.99, if there are 10 such surfaces, the signal is reduced by 0.9 and even in the best designed system, such as MROI [4], there are at least 15 mirrors. Other interferometers have more than double that number of mirrors.

Despite the difficulties, this method has been very successful in stellar imaging and simulations hold promise for the imaging of GEO satellites.

## 4. IMAGING TECHNIQUES

*Imaging with large apertures*

The imaging properties of any telescope are limited by the size of the collection aperture which defines both the light collecting properties (which scales as $D^2$) and the resolution (which scales a 1/D). However increasing the diameter is costly (with scales as $\sim D^{2.7}$) [5]. Presently there are 13 facilities around the world that have telescopes with effective apertures of 8.0m or larger, the largest being the Large Binocular Telescope (LBT) on Mount Graham in Arizona which uses a pair of 8.4m mirrors mounted on a common base [6]. Each borosilicate honeycomb mirror represents the largest single monolithic glass telescope mirror. The binocular design of the LBT has two identical 8.4 m telescopes mounted side-by-side on a common altitude-azimuth mounting for a combined collecting area of a single 11.8 m telescope. The two primary mirrors are

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separated by 14.4 m center-to-center and provide an interferometric baseline of 22.8 m for diffraction-limited observations. Effective apertures greater than 8.4m have been realized by using segmented optics. For example the Keck Observatory on Mauna Kea on the Big Island of Hawaii is comprised of a pair of telescopes (Keck 1 and Keck 2) each of which has an effective aperture of 10m [7]. Each 10m aperture is really 36 closely packed hexagonal segments, each 1.8 m wide.

While larger apertures, which are required to collect light from fainted objects such as GEOS and to provide better resolving power, will continue to get larger, this growth time-line will be slow due to cost. To utilize these larger apertures for imaging requires special adaptive optics since typically, even at sites like Mauna Kea, a site with very good atmospheric seeing, have effective r0 on the order of 20cm or less in the visible.

*Imaging with a Sparse Array*

Another way to achieve large effective apertures is to use a sparse array concept coupled with interferometry. This techniques was initially developed by the radio astronomy community but was then applied to optical (visible and near IR) spectral region (Keck, VLTI, NPOI, CHARA MROI arrays amongst others) [7, 8, 9, 10, 11]. An interferometer array is just a pair of apertures where light collected from each is combined to extract the complex visibility. Using three such apertures can eliminate the need for costly adaptive optics by employing phase closure, which utilizes the fact that the light collected from the three individual apertures all experience common atmospheric turbulence which alter the fringe pattern from any given pair. If the three complex visibilities are multiplied to form what is called a triple product the common atmospheric phase term subtracts out.

The advantage of interferometers is that a large effective aperture can be obtained with a few small apertures. One disadvantage of interferometers is that, except for the MROI which is model independent, they are dependent upon *a priori* models of the target being imaged.

The MROI [11], for example, capitalizes on both significantly enhanced sensitivity compared with existing ground based interferometer arrays and also on significantly higher (> 10×) resolution as compared to any ground-based AO-corrected telescope likely to be deployed in the next 10–20 years. It is estimated that with the full 10-telescope complement of the MROI it will be routinely possible to make images containing approximately 50 independent resolution elements. Depending on the precise array layout being used, these could distinguish, for example, 70 cm features on a 5-meter bus and payload, or 30 cm features on a satellite or piece of space debris, a factor of roughly two times smaller.

*Speckle Imaging*

Images of objects in space, GEOS as well as stellar objects, are blurred by turbulence. If you take a photographic image of the star the resulting image is blurred due to the multiple realizations of the atmospheric turbulence which changes on a time scale of about 10ms [2,12].

**Figure 1 - Simulation results showing a short (left) and long (right) exposure of a star through turbulence. Turbulence strength was estimated with D/ro =10. These results you can 'freeze' the turbulence and get a clearer image. However, the short exposure image on the left, is speckled which result from the interference of light from many coherent patches, each with a diameter of about r0, distributed over the full aperture of the telescope. [13]**

The number of speckles Ns per image is defined by the ratio of the seeing patch ~ λ/r0 to the area of a single speckle

$$Ns = (\lambda/r0)^2 / (\lambda/D)^2 = (D/r0)^2 \quad (6)$$

This can typically be 1000 Ns, the number of speckles in a single short exposure.

Labeyrie [14] first showed that for the case of short exposures, the image intensity distribution is related to the object distribution by a convolution with the transfer function of the atmosphere and the telescope.

$$I(u) = O(u) \cdot S(u) \quad (7)$$

The autocorrelation in image space corresponds to the power spectrum in Fourier space

$$|I(u)|^2 = |O(u)|^2 \cdot |S(u)|^2 \quad (8)$$

Where $|O(u)|^2$ is the object power spectrum and $|S(u)|^2$ is speckle transfer function. Rearranging for $|O(u)|^2$ and taking the time average leads to Labeyrie's conclusion that the time averaged speckle transfer function is derived from the ensemble instantaneous measurements. That is taking, an average of short exposures, each with minimized atmospheric contribution leads to reconstruction of Fourier amplitudes.

$$|O(u)|^2 = \langle |I(u)|^2 \rangle / \langle |S(u)|^2 \rangle \quad (9)$$

This work resulted in some very good results for imaging stars but really required a priori knowledge of positivity, i.e., the intensity profile is everywhere positive and that the image could be bounded.

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Extension of the work of Labeyrie led to two other methods: Knox-Thompson [15] and Triple Correlation [16]. Unlike Labeyrie, which really only recovers Fourier modulus information from the objects autocorrelation, Knox-Thompson and Triple Correlation allow for the recovery, in certain instances, of the phase and thereby recover a full image which is more useful for the imaging of GEOS.

*Hyper-spectral Imaging*

With hyper-spectral imaging the sensor breaks the electromagnetic spectrum up into many separate wavelength regions and when combined for a particular object can provide a unique fingerprint for that object. Hyperspectral imaging is presently being used from an experimental satellite imaging the earth's surface to look at vegetation distribution [17]. There have been efforts to look at using hyperspectral imaging to learn information about a satellites mission from hyperspectral information about the materials that make up the satellite. At the present time this is still in the research stage but hyperspectral information can be used in conjunction with other imaging information to expand the knowledge set about a particular satellite

## 5. UNCONVENTIONAL IMAGING METHODS

With conventional imaging the optical system relies on refractive or reflective optics to form a two dimensional image in the focal plane. Unconventional imaging on the other hand is basically 'lens less' imaging since there is no reliance on an imaging lens. Since the passive signal in the pupil plane is generally weak these methods have utilized laser illumination.

When the objects of interest are in low (LEO) or geosynchronous (GEO) earth orbit these unconventional methods of imaging that rely on active illumination are potentially possible. These unconventional imaging methods have been examined for nearly two decades and use active illumination and collected the reflected light in the pupil plane. There have been several proof-of-principle demonstrations carried out to demonstrate the ability and limitations of unconventional imaging and how they might take advantage of the large astronomical systems in place. [18, 19]

*Laser Speckle*

The simplest unconventional imaging method is laser speckle correlography [20, 21]. When the object is illuminated by a laser, the fully developed speckle pattern formed by the coherent interference of the backscatter, the reflected laser light that illuminates the target, from a diffuse target contains details of the illuminated surface. Each realization of the observed speckle intensity can be written as the square of the modulus of the complex field.

$$\mathrm{I_n(u)} = |\mathrm{F_n(u)}|^2 = |\mathrm{FFT}\{\mathrm{f_n(x)}\}|^2 \quad (10)$$

and

$$\mathrm{f_n(x)} = |\mathrm{f_0(x)}|\exp[\mathrm{i}\varphi_\mathrm{n}(\mathrm{x})] \quad (11)$$

is the field reflected by the object; $|f_0(x)|$ is the object's field amplitude reflectivity, and $\varphi_n(x)$ is the random phase of the $n^{th}$ realization of the reflected object field associated with the objects surface profile. In this example x is a two dimensional coordinate on the object and u is the two dimensional coordinate in the measurement plane which would be the pupil of a telescope that is in the far field of the object. Fourier transforming the two dimensional speckle pattern is proportional to the autocorrelation of the objects field. An iterative algorithm is needed to deconvolve the telescope aperture function and reconstruct the two dimensional complex-valued speckle image. The Air Force has conducted experiments of this approach on objects in LEO but it was only successful only for a select class of objects where a priori knowledge about the object is known.

*Sheared Beam Imaging*

This approach was much more successful in providing images of LEO object. It is a little more complex in that the object is illuminated by three coherent laser beams each with a slightly different frequency and displaced with respect to one another by a shear distance. The frequency offset is selected such that there is a beat frequency, a sweeping interference pattern that moves across the object for each pair of beams and the shear is matched to the detector spacing in the receiver array. A fast detector then samples the beat frequencies on each detector. The AC part of the beat frequency is measured which is extracted from the intensity measurements. This gives

$$\mathrm{E}(\vec{\mathrm{x}}) \cdot \mathrm{E}(\overrightarrow{\mathrm{x}+\mathrm{S}}) \quad (12)$$

which is complex. An iterative non-linear reconstructor then determines $E(\vec{x})$ ·which is the complex field of the target. Since the measurement is determined only from the intensity of the return signal the image is not degraded by atmospheric turbulence

The Air force Research Laboratory (AFRL) Active Imaging Testbed (AIT) program [22, 23, 24] culminated in the late 1990s with ground to space imaging of several LEO targets and achieved an on target resolution of 30cm at 1000km. In this program a version of sheared beam called DCbeam was used which looked at the depolarization from the target illuminated by a single beam. This process had the advantage that it simplified the transmitter but required at polarimeter to calculate the Stokes vector of the return signal. The $E(\vec{x})$ ·was then extracted from the four Stokes vectors. A sample of a result is shown below.

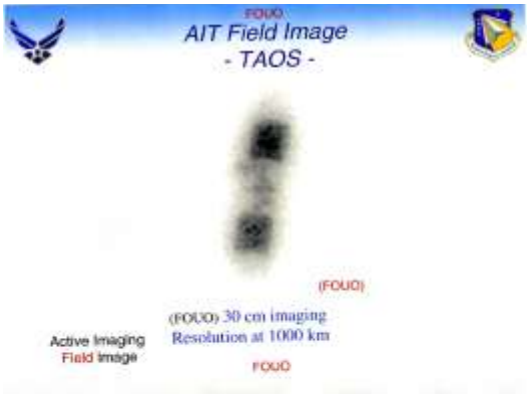


**Figure 2 - An example of a Sheared Beam image.**

*Fourier Telesopy*

Fourier Telescopy (FT) is an interesting active imaging technique in that it is very much like long baseline interferometry in reverse [25]. Long baseline interferometry utilizes an array along a long baseline consisting of small telescopes that each collects light form the same object. The collected light from each of the individual telescopes is then allowed to interfere on a fringe imaging detector. The interfering signal from each triplet (each triplet results from the interference from the three pairs of telescopes) allows three components in the uv plane to be determined without complication from the atmosphere degrading the phase. The image is then determined from the Fourier transform of the set of uv plane components. If enough baselines are sampled then the full uv plane can be determined and the object is then obtained from the Fourier transform. In FT an array of laser broadcast apertures are setup and a laser beam is broadcast simultaneously from 3 apertures at once and they interfere on the target. The signal is then collected with a single aperture, which can be a simple light bucket, large aperture telescope and single detector. This signal then corresponds to one component in the uv plane. Then a different triplet of broadcast apertures illuminate the target and its signal is collected and mapped to a different point in the uv plane. It is evident that since each triplet is broadcast one at a time this method would not work for a LEO object where satellites cross the sky in a short time. There has been a version of FT demonstrated where multiple triplets are broadcast at once that could accommodate imaging a LEO object.

With three broadcast sources illuminating a target each from different ground positions and each with a slightly frequency, the return measured quantity is

$$M_{ij} = c \cdot O(k_i - k_j)\exp(i\Delta\omega t + i\varphi_i - i\varphi_j) \quad (13)$$

Where $i \neq j$ both correspond to the pair of broadcast transmitters and to $k = \frac{k_0 \vec{x}}{\vec{z}}$

The three measured quantities are

$$M(k_1) = M_{1,0} = c \cdot O(k_1 - k_2)\exp(i\Delta\omega t + i\varphi_1 - i\varphi_0) \quad (14a)$$

$$M(k_2) = M_{m,1} = c \cdot O(k_m - k_1)\exp(2i\Delta\omega t + i\varphi_m - i\varphi_1) \quad (14b)$$

$$M(k_3) = M_{m,0} = c \cdot O(k_m - k_0)\exp(3i\Delta\omega t + i\varphi_m - i\varphi_0) \quad (14c)$$

By forming a triple product, the phase unknown phase terms disappear. This is the same as phase closure in stellar interferometry. A demonstration of this process was conducted at White Sands Missile Range by Trex Enterprises [18]. In the demonstration a laser illuminated a target with sets of triplets that had the same angular extent as illuminating a GEO target from the ground. The reflected light traversed a 1.5km horizontal path to the detector where it was processed to form the image.

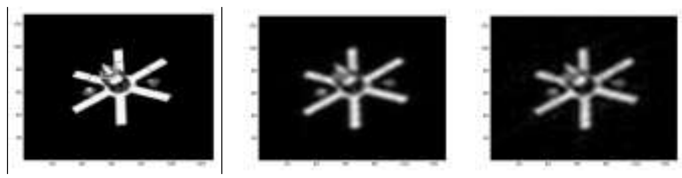

**Figure 3 - The truth object is on the left, the diffraction limited reconstruction in the middle, and the reconstructed image on the right.**

This program successfully demonstrated that by illuminating with triplets phase closure allowed the image to be reconstructed without any degradation form atmospheric turbulence.

## 6. ACTIVE ILLUMINATION

*Link budget and power/energy requirement*

Since the goal of this paper is to look at GEO imaging methods and we have described unconventional imaging techniques that require laser illumination, the appropriate question to ask is how much laser power (or energy) is required. The energy received from a GEO target illuminated by a laser of energy $E_B$ is given by:

$$E_{rec} = E_B \cdot \eta_{trans}{}^2 \cdot \frac{\rho_{tar}}{\pi} \cdot \frac{A_{tar}}{Abeam} \cdot \frac{A_{rec}}{R^2} \cdot \eta_{tr\ optics} \cdot \eta_{rec\ optics} \quad (15)$$

where $E_B$ is the broadcast energy (here we are assuming a pulsed laser format), R is the distance to the target, $\lambda$ is the broadcast laser wavelength, Abeam is the laser broadcast beam at the target (here we are assuming a Gaussian beam profile), $\eta_{trans}$ is the transmission through the atmosphere and is squared to account of the uplink and downlink, $\rho_{tar}$ is the reflectivity of the target into $2\pi$, $A_{tar}$ is the cross-sectional area of the target, $A_{rec}$ is the receiver collection area, $\eta_{tr\ optics}$ accounts for the losses in the transmitter and $\eta_{rec\ optics}$ accounts for the losses in the receiver. The Gaussian laser beam profile is given by

$$\text{Abeam} = \left(\frac{1.22 \cdot \lambda \cdot R \cdot BQ}{D_{tr}}\right)^2 \quad (16)$$

When $D_{tr}$ is larger than r0 and with no adaptive optics then it is replaced by r0.

*Implementation*

It is not likely that any of the active imaging techniques which require laser illumination will be allowed to be broadcast out of any of the large telescopes listed in this paper. Especially when the goal is imaging GEO targets which could require very high laser powers. Possibly a smaller broadcast aperture that illuminates the object of interest and the large aperture telescope serves as the receiver could be set up.

Mirror technology reached its limit with the 5-meter diameter mirror of the Hale telescope on Mount Palomar which uses a single piece of glass. This size is about the limit for such a mirror. Larger single piece glass mirrors will not be able to maintain any figure on the surface due to strain resulting from its own weight. In addition, large monolithic glass mirrors require a time to adjust to the ambient air temperature and because of slow thermal contraction or expansion the ability to focus the telescope is impaired. Large glass mirrors are very heavy and require large, complex mechanical support systems.

With the advent of fast control systems coupled with active and adaptive optics, large telescope made out of segments are possible. And today there are several large telescopes made up of segments.

## 7. CONCLUSIONS

With the ever increasing need to observe objects in GEO with high resolution, unconventional imaging methods hold promise. However, the fact that these require active illumination will always make it difficult to implement. Facilities such as AEOS (and its sister facility, the 3.5m telescope at SOR) and the SST have been test beds for various novel focal plane and pupil plane methods in and attempt to enhance focal plane imaging. In addition, a new generation of interferometric arrays, like the MROI, offers an ability to image these GEO targets without active illumination [26]. The use of a sparse array with extended baselines combined with a single smaller telescope to fill in the missing uv information is a particularly promising approach.

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