Sheared Coherent Interferometric Photography
A Technique for Lensless Imaging

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ABSTRACT

A new active imaging technique is described which eliminates atmospheric distortion and can give diffraction limited performance without any focusing optics. It has been demonstrated in computer simulations and laboratory experiments.

2. INTRODUCTION

Back in 1983 when the new technology of adaptive optics was producing its first successes in Maui with the new Compensated Imaging System and SDI demonstrations, Itek Optical Systems began considering other imaging techniques which could also cancel the atmospheric distortions but which did not require the expense of deformable mirrors and wavefront sensors. The result of this research was first a technique called Pulsed Laser Photography and then a successor called SCIP which turned out to be well suited to several different imaging missions.

This paper describes the SCIP technique as well as some of its limitations.

3. DESCRIPTION OF SCIP

3.1 Speckled light

SCIP is an unconventional imaging system which observes the speckled pattern of light returning when an object is coherently illuminated by a laser as shown in Figure 1. The speckle pattern is a random complex distribution with zero mean which contains all the image information about the object. It is this same pattern that is recorded in a hologram. Detectors usually see only the intensity of the pattern which has a probability distribution where zero is the most likely value. Other intensities have exponentially less probability which means that the speckle pattern is full of drop outs, and the highlights are often 6 times the mean intensity.

If this speckle pattern is somehow measured in magnitude and phase, then the coherent image can be formed by a computer simply by taking the fourier transform of the complex data and squaring it to give intensity. This is exactly what a lens does optically. However, the image formed is itself heavily speckled (same exponential intensity distribution) and looks very noisy. This coherent image must be averaged over 50-100 different frames before it begins to look like a familiar incoherent "white light" image.

This averaging process where many speckle frames are summed also happens in a normal camera, but there the bandpass is so large that speckle averaging occurs in less than one microsecond.

0-8194-1278-3/93/$6.00

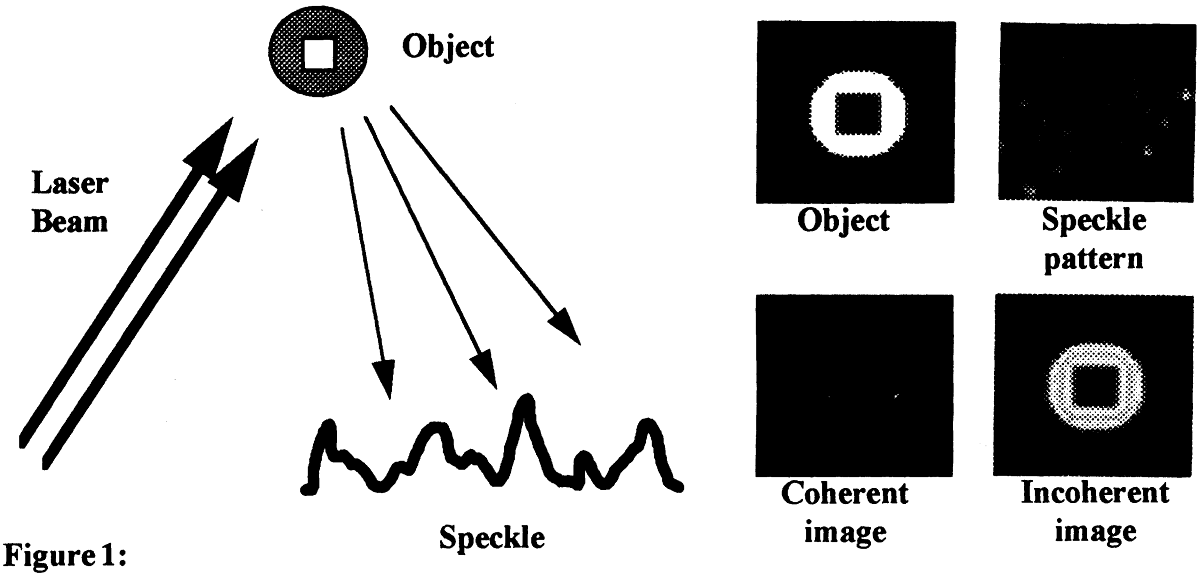


Figure 1:

- Laser illumination of an object returns a randomly varying complex field
- Speckle pattern contains all object image information
- Squared fourier transform is coherent image
- Averaged coherent image is incoherent image

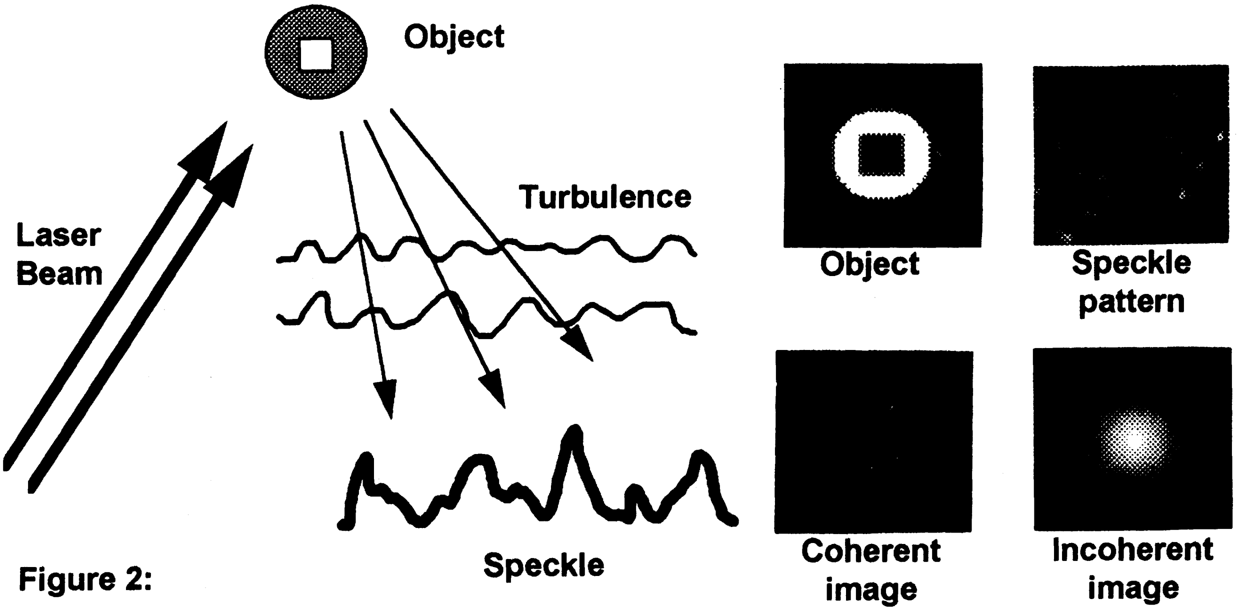


Figure 2:

- Distortion in the medium preserves the speckle intensity but scrambles the phase
- Resulting coherent and average images are severely degraded
- SCIP process encodes the speckle information to make it immune to turbulence

3.2 Atmospheric distortion

When light passes through the atmosphere, the main effect is usually to scramble the phase while retaining the intensity distribution almost unaffected. This means that if one were to observe a speckle return through the atmosphere from an airplane or satellite, the speckle intensities would look unchanged -- as shown in Figure 2. However, if we tried to image such a pattern we immediately would see that the coherent and averaged (incoherent) images have substantially blurred -- usually to the point where the object is unrecognizable.

The problem addressed by SCIP is how to recover the scrambled phase information for the speckle pattern.

3.3 Translating a Speckle Pattern

One key concept to SCIP is to understand the effect when the illuminating laser beam changes direction. It turns out that a speckle pattern behaves very much like the return from a mirror as shown in Figure 3. If the angle of incidence shifts, then the angle of the return shifts an equal and opposite amount. This means that if an object is illuminated by two laser beams from different directions, then both beams return the same speckle pattern except that they are translated by a distance equal to the angle between the beams times the distance to the object.

Another key feature of this dual illumination geometry is that the phase relationship between the two returning speckle patterns is largely unaffected by the distortion in the medium. Since the rays from the object to the sensor follow the same path through the atmosphere, they both pick up the same phase aberration. Thus the phase difference between the two speckle patterns is unchanged and can be measured directly if we introduce a frequency shift between the two illuminating laser beams so that they beat together. While this phase difference is not the phase of either speckle pattern and cannot be used to make an image by itself, it can be used to recover the speckle phase.

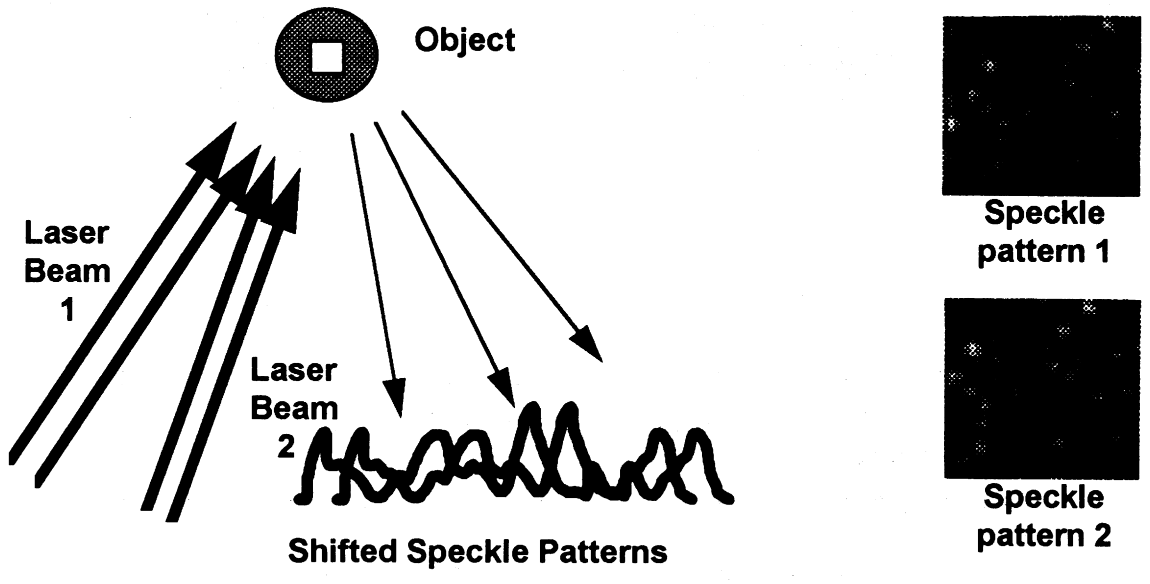


Figure 3: Two beams illuminating an object from different directions return the same speckle pattern - translated.

3.4 SCIP technique

The basic SCIP technique is to illuminate an object with three frequency shifted laser beams from three different directions as shown in Figure 4. One beam is called the main beam and often has 50% of the power. A second beam is shifted slightly in the x direction with 25% of the power, and a third beam is shifted slightly in the y direction with the last 25% of the power. This particular power ratio often gives the best SNR performance in the measurements.

The three returning speckle patterns are all identical but translated -- one in the x direction, one in the y direction and one untranslated. They retain their correct intensities and also their correct phase relationship despite having passed through turbulence. This means that a small detector would then see three beat frequencies between the three returning speckle patterns which could be analyzed for magnitude and phase. At each position (x,y), it then becomes straightforward to measure the x and y "gradients" of the speckle pattern. If we denote the complex amplitude of the main speckle pattern as A(x,y), then the three types of measurements which can be made are:

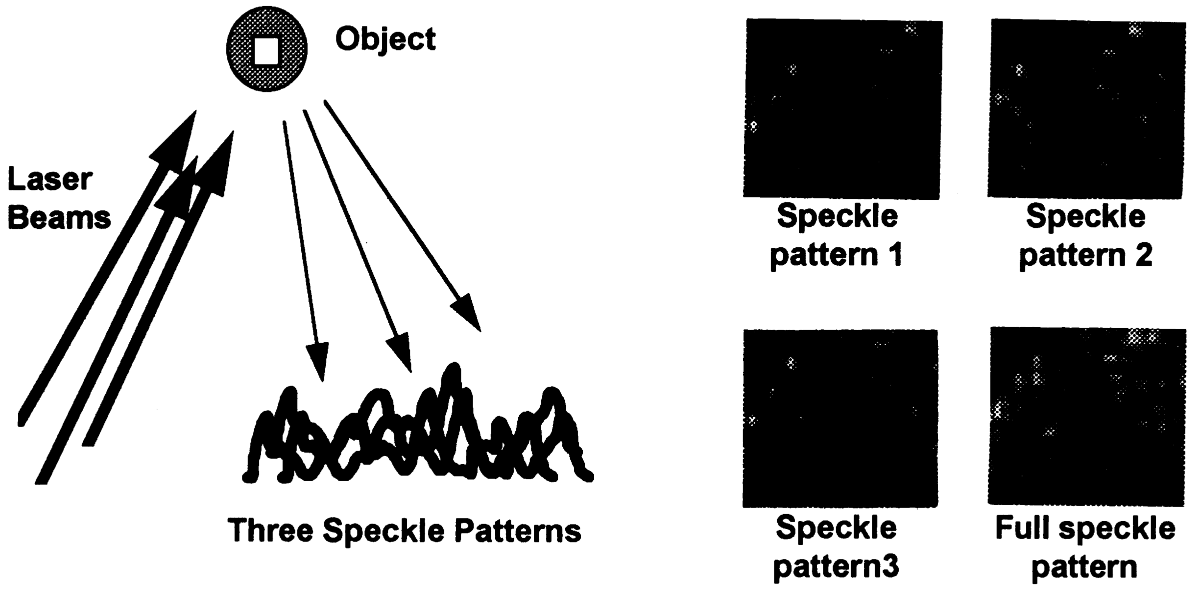


Figure 4:

- **SCIP illuminates the object with three frequency shifted beams at once**
- **Returning patterns are shifted about 1/2 speckle in x and y directions**
- **Phase relationship faithfully preserved between patterns - even through turbulence**
- **Demodulated beat signals measure complex product of shifted amplitudes**
  - $X(x) = A(x)\, A^*(x+s_x)$ $\quad$ $Y(x) = A(x)\, A^*(x+s_y)$

$$X(x,y) = A(x,y)\ A^*(x+s,y) \tag{1}$$

$$Y(x,y) = A(x,y)\ A^*(x,y+s) \tag{2}$$

$$C(x,y) = A(x+s,y)\ A^*(x,y+s) \tag{3}$$

There are three possible measurements -- one for each beat frequency, but usually only the first two (with the highest SNR) are used. The task is now to use these measurements to solve for the desired complex amplitude A(x,y).

3.5 Complex reconstruction

It is a familiar problem in adaptive optics to measure the gradients or phase differences of a wavefront aberration and then to "reconstruct" the actual wavefront with noise-optimized two dimensional integration. The same basic process applies to SCIP except that the algorithm must accommodate the extreme intensity (and SNR) fluctuations in the data as well as the complex nature of the speckle pattern. Usually it is not possible to find a real, continuous phase that matches the phase of any speckle pattern. Speckle patterns are inherently continuous but only as complex variables. They are full of cuts and whorls.

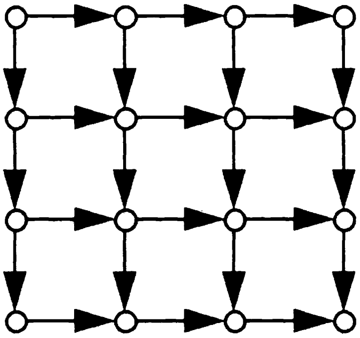
Fortunately Dennis Ehn of Itek had developed a suitable complex reconstruction technique around 1982 called Exponential Reconstruction for use in Knox-Thompson imaging which measures gradients in the fourier components and then reconstructs the entire fourier plane. While that process is completely different from SCIP, the same reconstructor was exactly the right tool to solve for the speckle amplitude A(x,y) given the gradients X(x,y) and Y(x,y). Ehn had also formulated the reconstructor very efficiently so that it only took about 20 complex operations per point to reconstruct the speckle pattern.

The reconstruction algorithm is shown conceptually in Figure 5 where different equations are used for the phase and magnitude of the speckle pattern. The phase of one point is related to the phase of its four nearest neighbors using the measurements X and Y, and the magnitudes of the signals are simply products of neighboring magnitudes. These equations can be solved by relaxation (which is very slow) or by the very streamlined exponential technique developed by Ehn.

3.6 Illuminating through the atmosphere

For the SCIP technique to work, the three beams illuminating the object must have nearly identical wavefronts -- to about $\lambda/14$ rms. One might wonder how such identical beams can be created when they traverse different paths up through the atmosphere. Fortunately, nature helps with diffraction. Basically, any beam of size 0.2 - 2 times the turbulence coherence length (r_0) diffracts out to give a nearly perfect wavefront in the central core as shown schematically in Figure 6.

Such a diffraction smoothed beam can be used effectively in SCIP as long as the object fits entirely within the central lobe. It turns out (perhaps surprisingly) that the intensity profiles of the beams are not very important, which means that considerable pointing jitter is acceptable as long as the central lobes hit the object. Even factors of two or more differences in intensity seem to have little effect on the quality of the image.



$$
\begin{aligned}
\phi(x,y) = \mathrm{Phase}[\, & X(x,y)\, A(x+s,y) \\
& + X^*(x-s,y)\, A(x-s,y) \\
& + Y(x,y)\, A(x,y+s) \\
& + Y^*(x,y-s)\, A(x,y-s)\,]
\end{aligned}
$$

$$M(x,y)\, M(x+s,y) = \mathrm{Mag}[\, X(x,y)\,]$$

$$M(x,y)\, M(x,s+y) = \mathrm{Mag}[\, Y(x,y)\,]$$

Figure 5: A set of 2D equations is solved to find the vacuum field using a fast numeric algorithm which requires about 20 complex operations per grid node

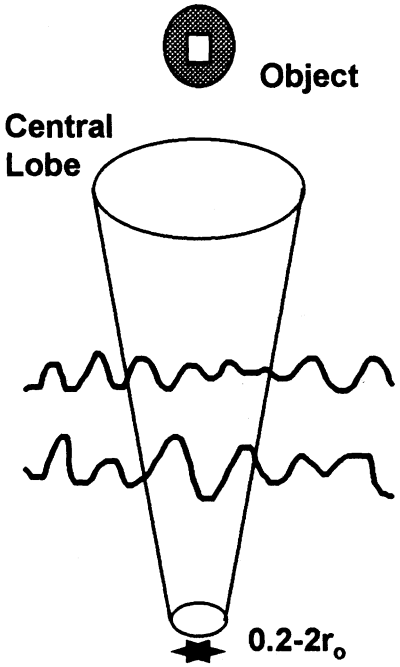


Figure 6: A uniform illumination beam can be produced through turbulence using a transmitter aperture diameter in the range 0.2 - 2 r_o

3.7 SCIP process

The SCIP process in total consists of six steps as summarized in Figure 7. First the object is illuminated by three frequency shifted beams coming from slightly different directions -- all of whose wavefronts are nearly identical. Second, the returning speckle patterns beat together and are sampled at a grid of points spaced by no more than 2/3 of a speckle size. This speckle size is just the wavelength divided by the angular size of the object. Third, the AC data is demodulated to give the magnitude and phase of X and Y speckle gradients. Fourth, these gradients are reconstructed to give the complex amplitude of the speckle pattern. Fifth, the speckle pattern is fourier transformed and squared to give the coherent image of the object. Sixth, a set of coherent images are averaged to give the final incoherent "white light" image.

Unlike some other imaging algorithms, the SCIP technique makes no assumptions about object bounds or statistics. It has often been called a deterministic process because the data determines a unique speckle pattern which can be directly calculated.

• Illuminate object	$I_{object}(\alpha_x,\alpha_y)$
• Record beat data	$I(x,y,t)$
• Demodulate data	$X(x,y,t)$, $Y(x,y,t)$
• Reconstruct pattern	$A(x,y,t)$
• Fourier transform and square	$I_{coherent}(\alpha_x,\alpha_y)$
• Average images	$I_{incoherent}(\alpha_x,\alpha_y)$

Figure 7: The basic SCIP process proceeds in six steps.

4. SCIP PERFORMANCE REQUIREMENTS

During the years of analysis, simulation and testing, several guidelines have been formulated which assure the best (near diffraction limited quality) from a SCIP system. They are listed in Figure 8 and begin with the three illuminating beams having identical wavefronts to $\lambda/14$ rms. As mentioned above, the beam intensities are not critical but the beams must flood the target or be superposed well enough so that the wavefront condition is met across the entire target area.

SCIP can be done at fairly low light levels (although the very low light level algorithms are not presented here). An individual speckle pattern can be estimated to about $\lambda/20$ rms noise with an SNR of 5

- **All three beams must have identical wavefronts to about $\lambda/14$ rms**
- **Intensity profile not critical**
- **Beams must flood target or be superposed +/- 20% of the central lobe**
- **SNR > 5 per subaperture**
- **Subaperture size <2/3 speckle size of $\lambda R/d_{object}$**
- **Distance between beam apertures should match subaperture size (or integer multiple) within +/- 20% of a subaperture**

Figure 8: SCIP requirements for diffraction limited performance

- **Fast, complex reconstructor Itek 1982**
- **Basic SCIP technique Itek 1984**
- **Lab demonstration Itek/DARPA/RADC 1986**
- **Synthetic aperture technique OPC 1987**
- **Synthetic ap demonstration AF Phillips Lab 1990**

Figure 9: List of major SCIP milestones

per subaperture (i.e. per detector element). This corresponds to about 25 photoelectrons per subaperture when a quantum limited detector is used.

Other restrictions are that the subaperture size should be no larger than about 2/3 of a speckle size (equal to the wavelength divided by the angular size of the object) and that the illuminating beams should cause a speckle translation equal to the subaperture spacing +/- 20%. Larger translation errors can be mitigated by processing, but best performance requires +/- 20% accuracy. This speckle shift is normally accomplished by physically moving the laser apertures apart by the desired translation and can be set precisely. However, the atmosphere does cause some beam wander which affects the speckle translation and reduces the number of frames with top quality when the speckles are small.

5. SCIP MILESTONES

Since this is the first open paper about SCIP, a short list of major historical milestones is included in Figure 9. It was first conceived in 1984 at Itek using the fast reconstructor technology developed a few years before. By 1986 the first lab demonstrations (funded by DARPA through RADC) had shown good quality images through distorting media. The next year SCIP was extended to use long pulse laser illuminators which allow the speckle pattern to sweep by and give a synthetic aperture.

After this came several years of quiet analysis and testing interspersed with system studies. Then in 1990 the AF Phillips Lab successfully demonstrated the synthetic aperture concept in the laboratory.

6. SCIP UTILITY

While SCIP was developed for military applications, it was recognized that significant commercial applications might exist whenever it is advantageous to image without lenses or through aberrating media. While such applications are only beginning to be explored, they include high resolution imaging with X-ray or gamma-ray lasers where imaging lenses would be very difficult to implement compared to simple observations on the scattered light. Other commercial possibilities involve acoustic imaging for medical diagnostics and geologic imaging for oil exploration. Both of those applications require imaging through distorting mediums and may benefit from SCIP.

7. SCIP SUMMARY

SCIP was developed to provide high resolution imaging through an aberrating medium without the cost of adaptive optics. It has achieved that objective and gathers its image data without precision optics. In principle, the detectors can be laid out as a large array on the ground, but in practice sky background considerations require at least the optical quality of a solar collector. This low optical quality contrasts to the high resolution achieved which is limited only by the size of the area covered by detectors.

SCIP has been analyzed and tested extensively at this point, and it is ready for routine operation as well as for commercial exploitation.

8. ACKNOWLEDGMENTS

This work has benefited substantially from insightful discussions with Mr. J. Richard Vyce and Dr. Dennis Ehn of Litton Itek Optical Systems and from the support of Dr. Shen Shay of DARPA and Dr. Donald Hanson of Rome Air Development Center. In addition, constructive criticism from Dr. David Fried and Dr. Glenn Tyler of the Optical Sciences Company helped mature SCIP into an operational technique.