# Multi-Channel Speckle Imaging

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## Contents

# 1 Summary

The basic idea of this proposal is to use the granulation of the solar photosphere as an encoder of speckle information to achieve interferometric image reconstructions for all kinds of narrow-band diagnostics of the solar atmosphere (filtergrams, magnetograms, Dopplergrams).

The technique of synchronous multi-channel speckle reconstruction from granulation was recently demonstrated by Keller and von der Lühe (1992). It furnishes appreciable increase (factor five) of spatial resolution over extended durations to a wide range of interests. The broad applicability derives from the ubiquity of granulation over the solar surface and throughout the optical spectrum and from its suitedness to speckle registration for slaved narrow-band data channels with too low $S/N$ for direct speckle reconstruction.

The factor five resolution increase represents improvement comparable to what will (hopefully) be reached by future adaptive optics. The method can be seen as adaptive optics *a posteriori*, or even as multi-conjugate adaptive optics *a posteriori* (Beckers 1989b) because there is no field limitation to the isoplanatic patch. The cost of the method is a large amount of post-detection computer processing. The powerful workstations now on the market make that viable.

The factor five resolution increase represents a breakthrough to optical solar physics. By going from $1''$ to $0.2''$ resolution in long-duration diagnostical sequences, solar physics comes close to the basic limits of scale heights and photon free paths (50–100 km; $1''$ corresponds to 725 km). It so passes a fundamental threshold in trying to understand physical processes in stellar atmospheres.

This proposal concerns the procurement of hardware and software systems to transit from pioneering demonstation to mature, productive routine application. Its goal is to build a multi-channel speckle imaging system for regular use on existing and future solar telescopes in the Canary Islands.

## 2 Speckle interferometry

For a good review of optical interferometry see Roddier (1988). Speckle interferometry has developed into a well-defined technique, regularly employed in night-time astronomy. Point sources produce speckles with the size of the diffraction-limited Airy disk. They dance around and boil away with the seeing. Fast monochromatic registration freezes them. Statistical analysis of many such specklegrams delivers the amplitude of the Fourier transform of the undisturbed intensity distribution, convolved with the speckle transfer function. The latter can be determined from a point source within the same isoplanatic patch of about $5''$.

The next step is to determine the phase of the Fourier transform of the undisturbed intensity distribution. This is less straightforward. Ingenious techniques have been developed, leaning heavily on radio-astronomy expertise (cross-spectrum analysis, phase closure, shift-and-add, Knox-Thompson, speckle masking).

The result is an estimate of the Fourier transform of the object, but affected by noise and missing components. Image reconstruction methods, similar to pattern recognition but in Fourier space, have been applied with varying success (Gerchberg, CLEAN, maximum entropy, Fienup).

Speckle reconstruction methods constitute a large literature. There is room for further sophistication and improvement, but the existing methods *work*. The major problem with night-time speckle interferometry is simply that the largest available apertures are too small. The resolution of a 4 m telescope suffices only for a very limited class of objects. Roddier (1988) noted that only about 150 papers described actual astronomical results, while he counted over a thousand papers on interferometric methods. This ratio improves, but speckle applications remain restricted to a few hundred objects (mainly resolvable binaries and circumstellar envelopes, see Perrier 1992).

The long-term prospects are better. Long baseline interferometry with sufficient collecting area and $(u, v)$ coverage, most notably in the VLT and Keck interferometry programs, should make optical interferometry much more productive, especially in the infrared where photon noise succumbs to speckle noise as limiting factor. Adaptive optics will help to increase isoplanatism. Eventually, a moon base (ESA's "Lunar Lunacy") may yield baselines of 1–1000 km and really sharpen our optical view of the cosmos. But that is far away.

## 3 High-resolution solar physics

The reason to be excited about solar speckle imaging *now* is that reaching the resolution of meter-class apertures represents an important breakthrough to solar observing. Current solar physics operates at the $1''$ limit, but many important processes and scales are set at the $0.1''$ scale size given by the photon mean free path and the density scale height in the photosphere. For the Sun, these scales are resolvable at 1 m baseline. Other stars require baselines a *million* times longer.

The emphasis in solar physics is on understanding time-dependent small-scale processes. The solar atmosphere is a very rich laboratory displaying an amazing variety of physics experiments in radiative transfer, hydrodynamics, magnetohydrodynamics and plasma physics. Every astronomer is aware that the solar surface looks awfully complicated (perhaps more so than he or she would like his or her more distant object to look); astrophysicists now begin to appreciate that the intricate structuring of the solar atmosphere furnishes a close-by, resolvable testbed of processes which are of interest to astrophysics in general.

Increase of spatial resolution is the major driver for most solar physics instrumentation developments[1]. It is important to note that this does not concern just white-light imaging, but obtaining differential two-dimensional narrow-band diagnostics in varied combinations. Solar processes and structures are highly time-dependent, are constrained by velocity fields and by magnetic fields, and extend with much variation from the subsurface layers to the outer heliosphere. They require high-resolution imaging in a number of spectral diagnostics, including filtergrams in lines from various heights (photosphere, temperature-minimum region, chromosphere, corona), Dopplergrams and magnetograms, also at different heights. These should be taken co-spatially and synchronously, in rapid but long sequencing. Such high-resolution narrow-band imaging in multiple spectral diagnostics is *the* frontier of optical solar physics.

Recent solar physics facilities at this frontier include:

- Canary Island telescopes:
    - Swedish Vacuum Solar Telescope (SVST, 48 cm) on La Palma
    - German Gregory Coudé Telescope (GCT, 45 cm) on Tenerife
    - German Vacuum Tower Telescope (VTT, 70 cm) on Tenerife
- real-time image-motion correctors employing active mirrors:
    - Lockheed (LPARL) pore tracker on the SVST
    - autocorrelation trackers on the VTT and the Sacramento Peak Tower Telescope (SPO-TT, 75 cm)
- narrow-band imagers:
    - SOUP tunable filtergraph on the SVST and the VTT (LPARL)
    - tandem tunable-filter/Fabry-Perot on the SPO-TT (NOAO)

[1]Excepting helioseismology (Antarctic, IRIS, GONG, SOHO projects). Temporal Fourier frequency resolution is the first requirement for these.

  - Stokes polarimeter on the SPO-TT (HAO-NCAR)
  - Zürich Stokes polarimeter on the SVST (ETH)

The Sterrekundig Instituut Utrecht participates in various of these programs, especially the yearly LPARL SOUP–SVST campaigns (Zwaan, Rutten, Strous, Balke, Hoekzema). These also involve Utrecht offspring at CfA and LPARL (van Ballegooijen, Uitenbroek, Martens).

Future optical solar physics facilities are, in probable order of realization:

- Canary Island telescopes:
  - Dutch solar telescope (OTT, 45 cm [82 cm], La Palma)
  - French solar telescope (THEMIS, 90 cm, Tenerife)
  - international solar telescope (LEST, 250 cm, La Palma)
- space telescopes:
  - SHARP (NASA, 20 cm, free flyer)
  - OSL (NASA, 100 cm, free flyer)
  - SIMURIS (ESA, 200 cm interferometer, Space Station)

The Sterrekundig Instituut Utrecht is involved in all three space projects. None is yet funded.

The present proposal fits beautifully in these developments. A robustly working narrow-band speckle imaging system capable of large-volume data handling enhances the science capability of the existing and future telescopes dramatically.

Let me briefly describe the current state of the art. Only occasional images reach the diffraction limit of a small telescope; that requires super-seeing which is rare even at the best sites. Brandt *et al.* (1987) specify that the Fried parameter $r_0$ (roughly the aperture of a telescope equal to the seeing quality) at SPO is between 3.5 and 20 cm 90% of the observing time. The sharpest solar images come from Pic du Midi (super-seeing only when snow falls in summer) and the SVST at La Palma. The latter telescope has probably the best optics of all solar telescopes (Scharmer *et al.* 1985). It also has a real-time video frame selector (Scharmer 1989) which "grabs" and stores the best video frame per preset interval, for example every 10 seconds. The 17 ms video exposure time nearly freezes the seeing. The grabber-selected frames are subsequently re-registered to take out image motion due to seeing and telescope shake, rubber-sheet deformed (image-to-image local autocorrelation) to correct large-scale seeing motions, and 3D Fourier-filtered in $x$, $y$ and $t$ simultaneously. The latter filtering passes subsonic motions only to take out fast small-scale seeing motions as well as solar $p$-mode oscillations. These procedures, mostly developed at LPARL, have generated the best granulation movies so far.

The frontier now lies in combining multiple narrow-band diagnostics in similar sequences. For example, LPARL's SOUP tunable filtergraph is used at the SVST to obtain long image sequences alternating between magnetograms, Dopplergrams, the H$\alpha$ chromosphere and the continuum photosphere in rapid succession, spewing data on to Exabyte cassettes. The long exposure times required for the narrow-band diagnostics (0.2–2 sec) result in much spatial smearing, even though a fast active mirror takes out whole-field image motion. As a result, only sporadic narrow-band frames pass the $1''$ limit; most are worse.

The multi-channel speckle restoration method described below improves the resolution of the narrow-band images by a factor of five over the average broad-band video frame quality, which is already much better than an average narrow-band exposure. The improvement is even larger if no active mirror is used, because the method also corrects for instantaneous image motion. The method makes it possible to regularly obtain long sequences of narrow-band images with the quality of the best broad-band granulation movies to date.

In moments of super-seeing ($r_0$ well over 20 cm) the proposed method will attain the resolution of meter-class telescopes. It is therefore also of large interest for the future, larger telescopes (OTT upgrade[2]; THEMIS; LEST). Note that narrow-band imaging with these telescopes requires the same long exposure times. The number of photons per telescope resolution element does not increase with the aperture. Multi-channel speckle reconstruction therefore improves narrow-band performance at *any* telescope up to its diffraction limit, as long as there is object structure with sufficient modulation at spatial scales up to that resolution. The solar granulation provides that for 1 m baseline, and probably for even longer baselines.

It would be easy to give a long list here of solar physics research programs to which the proposed speckle imager will contribute. It would be the same as the science descriptions for adaptive optics, LEST, SHARP, OSL and SIMURIS. Simply put, *any* appreciable improvement in diagnostic imagery of the solar surface promises large astrophysical returns.

At Utrecht, the expertise in optical solar physics can be summarized by "solar MHD = close-up astrophysics". There is strong emphasis on magnetic structuring, with much expertise in plasma physics, magnetohydrodynamics, radiation hydrodynamics, NLTE radiative transfer and field topology. A strong point is also the readiness to apply solar insights to other astrophysical circumstances (cool-star activity, flare stars, accretion disks). The multi-channel speckle imager, if available now, would immediately cater to Utrecht interests as:

- internetwork and network hydrodynamics (Rutten, Balke, Hoekzema);
- network structure and topology (Schrijver, Zwaan);

[2] David Rust (Johns Hopkins) has proposed installing an existing high-quality 82 cm mirror in the OTT. It fits in the present mechanical structure.

– active region structure and topology (Zwaan, Strous, van Driel);

– coronal structures and processes (Kuperus, van den Oord, Zwaan).

## 4 Multi-channel speckle reconstruction

Solar granulation provides a useful source of Optical Transfer Function (OTF) information. It can therefore take the role of bright stars as OTF encoder. Granules are not pinpoints on the sky, but they encode every isoplanatic patch within an image of the photosphere with suitable modulation at all scales and can be used to reconstruct high-resolution detail from the statistics assembled in a burst of specklegrams. Granulation combines:

– *spatial scale spectrum.*
  Granulation supplies multiple granules per isoplanatic patch, with structuring down to the diffraction limit of at least a 1 m telescope;

– *ubiquity over the solar surface.*
  There are granules in every quiet-Sun isoplanatic patch. Elsewhere, white-light plage, pores, penumbrae and umbrae also supply suitable small-scale intensity structure;

– *sufficient pattern duration.*
  Granulation doesn't change much over 10 s. Its apparent pattern motions are subsonic. The sound speed is 7 km s$^{-1}$, corresponding to $0.1''$ displacement over 10 s;

– *high $S/N$ detectability.*
  Broad-band (5–10 nm) continuum imaging gives good $S/N$ per telescope resolution element per 10 ms specklegram exposure;

– *ubiquity throughout the optical spectrum.*
  Any continuum window suits to observe granulation. It may therefore be chosen near the spectral line diagnostic. At longer wavelengths, OTF scaling may sometimes be feasible because the wavefront disturbances are geometrically achromatic above $\lambda = 500$ nm.

The constraints on specklegram acquisition are:

– *short exposures.*
  Exposure times of 10 ms or less, to freeze the wavefront;

– *numerous specklegrams per burst.*
  A total of 100–1000 frames, to obtain sufficient seeing statistics;

– *short burst duration.*
  Order of 10 s, shorter than solar structure changes at the resolution limit;

– *large $S/N$ per specklegram.*
  Order of 100, sufficient to register speckle information accurately.

The latter constraint forces broad-band observation, of order 10 nm. Diagnostic images such as chromospheric Ca II K filtergrams, H$\alpha$ filtergrams, CN bandhead filtergrams, Dopplergrams and magnetograms require much narrower passbands, of order 0.01 nm. Direct speckle restoration is impossible for these due to lack of $S/N$ (order 0.1). In addition, the solar scenes observed in such diagnostics do not provide structuring as suitable as the photospheric granulation does.

Thus, the factor 1000 in bandwidth implies that narrow-band diagnostics require 1000 times longer exposure to reach the same $S/N$ as granulation images. The latter require only 10 ms, which happens to equal the specklegram freezing time since seeing varies with frequencies up to 50 Hz. Speckle restoration requires many samples of the seeing to obtain good statistics. The photospheric surface patterns are stable over 10 s, so that a burst of 10 ms frames may contain 1000 specklegrams. These numbers fit beautifully: *building up sufficient $S/N$ in narrow-band diagnostics just fits the required specklegram burst duration.*

Clearly, the trick is to use the granulation as encoder for narrow-band image reconstruction. This is possible by splitting the long exposures needed for narrow-band $S/N$ in many short-exposure frames which correspond one-to-one with granulation specklegrams. The procedure then consists of:

– synchronous registration of specklegram bursts in the narrow-band channel(s) of interest, and in a broad band in the nearby continuum;

– reconstruction of the broad-band granulation scene per burst;

– reconstruction of the narrow-band scene using the broad-band OTF's.

This should be done per isoplanatic patch (about 5″ diameter) in the observed field. Every burst then delivers a sharpened granulation image and an *equally* sharpened image per slaved narrow-band channel, whatever $S/N$ is reached in the latter.

The method is in principle comparable to real-time adaptive optics correction of the wavefront and may be seen as competition to it. The above *a posteriori* reconstruction is obviously paid for in data stream size and off-line processing volume. The required frame rate is $N_{\rm ch} \times n_{\rm b}$ times larger than for direct exposures, with $N_{\rm ch}$ the number of channels (2 or more) and $n_{\rm b}$ the number of frames per speckle burst (100 or more). On the other hand, multi-channel reconstruction is not limited to the size of the isoplanatic patch (only a few arcseconds). Above all, *it works now.* Data handling can be automated.

Adaptive optics is still in the development stage. A prototype demonstration (Lockheed–NSO) has recently been achieved at the SPO-TT, sharpening a small pore. It requires the presence of such high-contrast structure within the isoplanatic patch, which limits the science objectives (the more so since solar activity declines the coming years). Daily application using low-contrast granulation as wavefront encoder for multiple isoplanatic patches is yet years away[3].

# 5 Demonstration

## 5.1 Method

Keller and von der Lühe (1992) have initiated the technique by using Scharmer's video imaging system (Scharmer 1989) on the SVST. They demonstrate the applicability by reconstructing images from a narrow-band continuum window within the broad band. The two reconstructions therefore display the same solar scene; the broad-band image can be used as gauge of the success of the narrow-band reconstruction. Results are shown in the next section.

Keller & von der Lühe used additional tricks:

- *image selection.*
  Scharmer's two-channel video frame "grabber" was used. Keller & von der Lühe used it to store the best of every 10 successive pairs. Much of the worse seeing is so eliminated; it makes the Fried parameter $r_0$ more homogeneous over the burst. This facilitates the reconstruction procedure.

  Such frame selection gives an appreciable increase of spatial resolution by itself, typically a factor 2 for 10% selection (unless the telescope itself spoils the image; the gain factor is a direct measure of telescope merit, see Beckers 1989a).

  Note that at the 16.7 ms video rate (alternate scan lines only), subsequent frames can differ much in seeing quality. Each frame freezes the instantaneous deformations; the next frame is a new sample. Atmospheric wavefront disturbances have Kolmogorov character, which makes for much variation. One frame may be sharp, the next one all blurred;

- *frame tessellation.*
  Since the frames are much larger than the isoplanatic patch, they were split into patch-sized segments and subsequently mosaiced back into full frames. This procedure extends speckle restoration to larger fields (note that frame selection probably increases isoplanatism, cf. Beckers 1989a).

Keller & von der Lühe reduced one 100–frame burst to demonstrate the method. They used the code of von der Lühe (1987) which estimates the Fourier ampli-

[3] The development of image motion correctors poses an analogon. These correct the instantaneous tilt of the wavefront in real time and may be seen as zero-order adaptive optics. Image trackers employing quad cells on pores have been in regular use for years already. Correlation trackers that employ the granulation to measure image motion have become fully operational only last year, after years of development (VTT, SPO-TT). They track only one isoplanatic patch, of course.

tudes with classical speckle interferometry and the Fourier phases with the Knox-Thompson algorithm. This was applied to the broad-band specklegrams. The narrow-band frames were deconvolved with the OTF from the broad-band restoration, with zero suppression through optimum filtering and noise estimation.

## 5.2 Results

The two figures on page 14 are copied from Keller and von der Lühe (1992). The first shows broad-band images, a sample frame at upper left (a), the speckle reconstruction from the 100–frame burst at lower right (d). The seeing was only "fair" (panels a and b); the Fried parameter $r_0$ was only 10 cm. The speckle reconstruction is much better, close to "excellent" seeing quality.

The second figure shows narrow-band results. The best single frame is at upper left (a). It is very noisy due to the limited spectral bandwidth (0.015 nm). The direct speckle reconstruction using the 100 narrow-band frames is at upper right (b). It should be compared with the broad-band reconstruction at lower right (panel d; the same as panel d in the top figure). There are significant differences. If one only had (b), one might believe all its detail; however, comparison with (d) shows that many features in (b) are unreliable. In contrast, (c) is nearly identical to (d). Panel c is the result from applying the OTF's from the broad-band speckle restoration to the narrow-band frames through deconvolution.

The very close agreement between (c) and (d) proves that the method works. The broad band supplies the $S/N$ to obtain a reliable result from narrow-band data. The improvement over the seeing quality (compare panels a and d in the top figure) is impressive. Note that (a) in the top figure is already better than average, because of the real-time frame selection. The best burst frame (c) is indeed not very much better; the average in (b) is not much worse. Note that the latter is a better average than a long exposure would have been, because image motion was taken out before averaging by reregistration of the frames.

The power spectra in the graph on page 15 (Fig. 4 of Keller & von der Lühe) quantify these results. The spatial frequency along the axis is normalized to the telescope diffraction limit of $0.22''$. The power spectra demonstrate the very good correspondence between the deconvolved narrow-band result and the broad-band speckle restoration. The cutoff frequency of the deconvolved image is twice the cutoff frequency of the direct narrow-band reconstruction.

In this demonstration the narrow band depicts the same solar scene as the wide band. Of course, the scenes may differ as long as the bands are sufficiently close in wavelength, the frames are taken synchronously and the fields are cospatial. The seeing is then shared, and the wide-band OTF's apply to the narrow-band frames whether these depict the chromosphere, Doppler velocity, Stokes $V$, or whatever else. Keller & von der Lühe proceed with a demonstration measuring Stokes $V$.

In summary, Keller & von der Lühe's narrow-band reconstruction using the broad-band OTF's comes very close to the broad-band speckle image, while the direct narrow-band speckle reconstruction shows many artefacts. Thus, multi-channel speckle restoration solves the $S/N$ problem for narrowband diagnostics. The spatial resolution is increased by a factor 5 or more. Half comes from the frame selection, the other half from the speckle restoration.

## 6 From demonstration to production

Obviously, to follow solar phenomena in time it is necessary to obtain, store and reduce speckle bursts in succession. Each speckle burst then delivers one image of a high-resolution movie. For example, using a two-channel speckle camera with SOUP at the SVST will result in solar movies of magnetograms, Dopplergrams *etc.* much as we take them now — but at least five times better. It has the effect of moving the SVST to a site which is five times better than the Roque de los Muchachos and where, in addition, image quality does not deteriorate with exposure time.

The method should now become a workhorse. This requires manpower, capital investment and organization. The needs are:

- *registration hardware.*
  Image selection system, cameras, camera controller, digitization, intermediate storage, transfer storage, final storage;
- *reconstruction and analysis hardware.*
  Fast workstations with fast graphics;
- *video storage, analysis and presentation equipment.*
  Frame grabbers, optical disks, recorders, display monitors, hardcopy facilities;
- *reconstruction software.*
  Speckle reconstruction, phase estimation, deconvolution, optimum filtering;
- *system management.*
  Data flow handling, project control.

On the registration hardware, efforts are required to assemble appropriate detection systems. The simplest solution is to videotape each channel on 8 mm cassettes, with off-line frame selection and digitization. The recording quality is probably much too low, however.

The next solution is Scharmer's video system at the SVST. Keller and von der Lühe 1992 used it successfully. However, it also poses problems:

- *8-bit registration.*
  The video system has only 8 bits, requiring careful adjustment of offsets and gains to use most of the small dynamic range. Contrast changes with time are hard to accommodate. A large dynamic range (12 bits) is desirable;
- *video rates.*
  Scharmer's COHU video cameras operate at 30 Hz, producing 16.6 ms exposures for single-scan frames. This is a bit long compared to seeing changes. Kneer and de Boer (Göttingen, unpublished) collect digital CCD speckle bursts of 100 frames with 4 ms exposures. A maximum of 10 ms is desirable;
- *storage capacity.*
  Scharmer's KONTRON image system only accommodates 17 Mb, equal to one two-channel burst of 150 frames each at $200 \times 240$ pixels per alternate-scan frame.

When using digital CCD cameras, the main issues are CCD readout speed and transfer speed and capacity of the storage media. The storage can be two-stage, using stacks of disks to be emptied overnight on Exabyte or DAT cassettes. The newest Exabytes recorders write 5 Gb cassettes at 0.5 Mb/s transfer speed (more with data compression).

Current CCD readout speed poses harder limits. A $1024 \times 1024 \times 12$ bits CCD camera has too slow readout at present. The LPARL SOUP filtergraph currently uses a $1024 \times 1024$ chip but it is usually pixel-binned to $512 \times 512$ to increase the frame rate. Specklegram registration requires a much faster rate again. However, hardware frame selection may decrease it by an order of magnitude.

A currently feasible option is to use fast frame selection and binning to limit the bursts to 100 frames of $256 \times 256 \times 12$ bits each, resulting in 20 Mb per two-channel pair, or 250 burst pairs per 5 Gb Exabyte cassette. At the maximum rate of 6 pairs/min, one cassette then corresponds to a 40 min image sequence. This is a good duration for monitoring fast changes. Likewise, data taking at 2–1 pairs per minute yields 2–4 hours per cassette; this is a sufficient rate for many programs because solar oscillatory power is negligible above 10 mHz frequency. A field of $256 \times 256$ pixels at $0.1''$/pixel ($0.2''$ resolution) cooresponds to a supergranulation cell, a much more reasonable field size to do solar physics on than the $4'' \times 4''$ or so which adaptive optics supplies. These figures are promising. In any case, initial limits to the pixel array size can be upgraded when faster transfer and larger-capacity storage become available.

The registration system can in principle be used at any telescope that enables feeding a wide-band granulation beam and one or more narrow-band diagnostic beams to different camera stations with good co-spatiality. Most solar telescopes (SVST, VTT, SPO-TT) supply their image to large optical tables on which such beam-splitter setups are easy. For example, the current LPARL–Utrecht observing with the SVST employs three such simultaneously operating data-taking stations. The first records the granulation with Scharmer's video system, the second Ca II $K_{2V}$ filtergrams, the third alternates between magnetograms, Dopplergrams, H$\alpha$ and Na I D filtergrams with the SOUP. Similar setups are also used at the German VTT. They would accommodate a multi-camera speckle imaging system without problem.

On the software side, developing a robust high-throughput system requires much work. This is the main body of the proposal. Setting up a regular system for speckle image processing is not the same as reducing a few bursts for demonstration. The effort will lie in constructing a smooth system for large-volume processing.

The required expertise may be developed through cooperation with others, such as von der Lühe (ESO), de Boer (Göttingen), Nisenson (Harvard), Scharmer (Stockholm), Shine (Lockheed).

A rough estimate of the project size is that it will need about 1 M$f$ for hardware (mostly computers) and 5 manyears effort (mostly electronics and software).

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