# POSTERS

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# The Stellar Imager and Seismic Probe (SISP)

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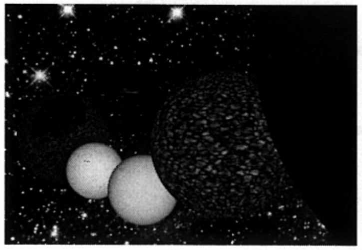
## Abstract

We describe a new mission concept for a space-based, UVoptical interferometer with 8 to 10 1 meter class apertures, a baseline > 0.5 km, and a central instrument hub. It will image the surfaces of other stars and perform asteroseismology for the purposes of improving our understanding of magnetic activity patterns and the solarstellar dynamo, to enable improved forecasting of solar activity and an understanding of the impact of stellar magnetic activity on life in the Universe.

# The Stellar Imager

[Also known as SISP: The Stellar Imager and Seismic Probe]

A voyage of exploration to understand the stars, the formation of planetary systems, and the existence of life



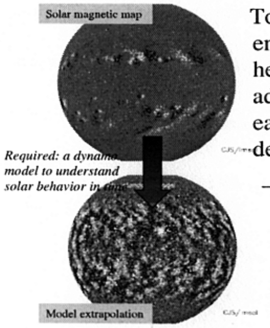
K. G. Carpenter (NASA/GSFC) and C. J. Schrijver (LMMS)

*Presented at the September 2000 NEVEC Interferometry Summer School in Leiden, The Netherlands*

## Primary Science Goals

- Study spatial and temporal stellar magnetic activity patterns in a sample of stars covering a broad range of activity level, in order to understand the underlying dynamo process(es) and thereby
  - enable improved forecasting of solar activity on time scales of days to centuries, including Maunder-like minima and "grand maxima" that significantly affect geospace and earth's weather
  - understand the impact of stellar magnetic activity on astrobiology & life
- Enable asteroseismology (acoustic imaging) to measure internal stellar structure and rotation and their relationship to the dynamo
- Complete the assessment of external solar systems
  - image the central stars of systems for which the Origins IR-interferometry missions find and image planets, and determine the impact of the activity of those stars on the habitability of the surrounding planets

## Value to Society:
## Space-Weather & Earth-Climate Forecasting



To understand past solar activity and to enable forecasting of solar and heliospheric activity days to decades in advance and anticipate its impact on the earth's biosphere and society, we need to develop and validate a dynamo model

- Testing grounds:
  - The Sun in detail
  - Population studies:
    - Stars like the Sun
    - Other ``cool'' dwarf & giant stars
    - Very young stars
    - Magnetically interacting binary stars

## Science Driver:
## Stellar activity is key to understanding life in the Universe and Earth's habitability

The stellar magnetic field

- slows the rotation of the collapsing cloud, enabling star formation
- couples evolution of star and pre-planetary disk
- results in energetic radiation conducive to the formation (& destruction) of complex molecules
- governs the habitability of the biosphere through space weather and planetary climate through luminosity, wind, magnetic fields, and radiation

- Problem: there is no comprehensive model of solar/stellar magnetic activity

## Science Requirement:
## Population Study of Cool Stars

- To understand the dynamo, we need to know how magnetic fields are generated and how they behave in different circumstances
- The sun is only one example
  - – provides insufficient constraints on theories of dynamos, turbulence, structure, and internal mixing
  - – must observe other stars to *establish how mass, rotation, brightness and age affect the patterns of activity* & determine:
    - What determines cycle strength and duration?
    - How common is solar-like activity?
    - Can multiple cycles exist at the surface?
    - What are Maunder-minimum states like?
    - How do polar spots form?
    - What are extremely (in)active stars like?

## Science Requirement: Asteroseismology

- Although its clearest manifestations are visible on the stellar surface, a full understanding of the dynamo requires a knowledge of the subsurface layers of the star in which it resides
- Asteroseismology (acoustic imaging) of the star enables us to address questions related to the stellar interior
  - – Where is the seat of the dynamo?
  - – What determines differential rotation and meridional circulation, and what role do they play in the dynamo?
  - – What is the impact of magnetic deceleration on internal rotation and stellar evolution?
  - – How are stellar interiors modified in extremely active stars?

## Primary Performance Goals

- Image different stars of different activity
  - – for a substantial sample of nearby dwarf and giant stars, obtain a resolution of order 1000 pixels ( ~50,000 km on a Sun-like star)
  - – study a sample in detail, revisiting over many years
  - – measure:
    - sizes, lifetimes, and emergence patterns of stellar active regions
    - surface differential rotation, field dispersal by convective motions, and meridional circulation
    - directly image the entire convection spectrum on giant stars, and the supergranulation on, e.g., the solar counterpart α Cen
- Enable asteroseismology, using low to intermediate degree non-radial modes to measure internal stellar structure and rotation.

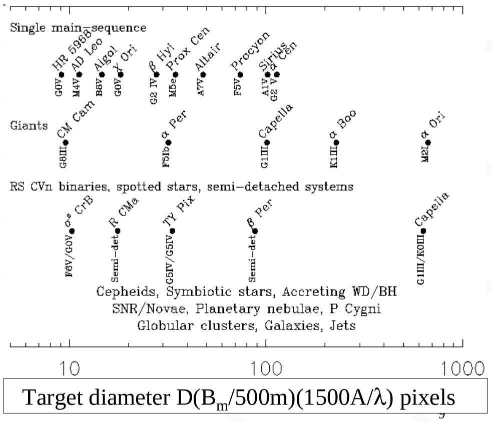
## Design Requirements

- Imaging of stellar activity requires
  - – High contrast at UV wavelengths
  - – Obtain a stellar image as fast as possible to avoid rotational smearing and activity evolution
- Imaging of stellar interiors requires
  - – Short integration times for seismology (minutes for dwarf stars to hours for giant stars)
  - – Low-resolution imaging to measure non-radial resonant waves (30-100 resolution elements)
  - – Flexible interferometer configuration

# Sample Targets

Sample target categories:

| | |
|---|---|
| χ Ori | Young Sun |
| β Hyi, α Cen | Solar analogs |
| HR 5968 | Maunder-minimum star |
| α Boo | Ancient Sun |
| Altair, Procyon, α Per | Onset activity |
| AD Leo, Prox Cen | Flare star; deep convection |
| CM Cam | Giant polar spot |
| Capella , σ CrB | Magnetically interact. binary |
| TY Pyx | Compact binary |
| R CMa, β Per | Semi-detached binary |
| α Ori | Supergiant star |
| Algol | Mass transfer |
| Sirius | Hot star |



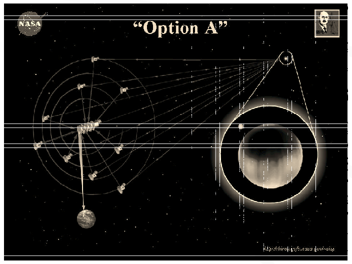
# Basic Strawman Design Elements

The Stellar Imager is a large space-based UV-optical interferometer, that provides a tool to astrophysicists of the same fundamental nature as the microscope to biologists, yielding

- an angular resolution of 60 and 120 micro-arcsec at 1550 and 2800
- ~ 1000 pixels of resolution over the surface of nearby dwarf stars
- largest telescope-pair baseline at least 500 meters
- observes in
  - ~10- ngstrom UV pass bands ($C^{3+}$ (100,000 K), $Mg^+$ h&k (10,000 K))
  - broadband, near-UV or optical continuum (3,000-10,000 K)
- telescope formation reconfigurable for synthesis imaging
- 5-10 year mission to study stellar activity/magnetic cycles:
  - individual telescopes/central hub can be refurbished or replaced as needed
- Array Configuration and Element Size/Type
  - Option A: ~10 1-meter class telescopes, plus central hub
  - Option B: ~30 1-meter class flat mirrors, plus central hub

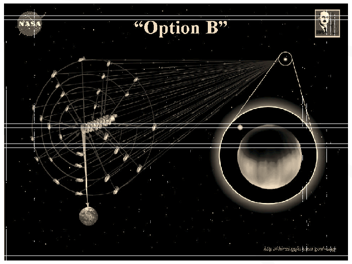
# Mission Concept A

- 9 or more 1-meter class telescopes as array elements
- central hub
  - telescope to provide zero-phase information
  - optics to combine and interfere beams (likely Michelson design)
- requires numerous reconfigurations of array to obtain synthesized image, but less complex hub than Option B



# Mission Concept B

- ~30 one-meter class flat mirrors as array elements
- central hub
  - telescope to provide zero-phase information
  - optics to reduce, combine and interfere beams (likely Fizeau design)
- requires fewer reconfigurations of array to obtain synthesized image, but more complex hub than Option A



## Place in NASA/ESA Strategic Roadmaps

- SISP on strategic path of NASA Origins interferometry missions
  - it is a stepping stone towards crucial technology…
    - SISP is comparable in complexity to the ***Terrestrial Planet Finder***, and it may serve as a useful technological and operational pathfinder for the ***Planet Imager:*** SISP resolution is ~40x less demanding than ultimate NASA goal
  - … while addressing science goals of 3 NASA/OSS research Themes
    - understand why the sun varies (SEC)
    - understand the origin of stars, planetary systems, and life (Origins)
    - understand the structure and evolution of stars (SEU)
  - it is complementary to the ESA & NASA planetary imaging interferometers
    - ***Terrestrial Planet Finder***, ***IRSI/Darwin***, and ***Planet Imager*** null the stellar light to find and image planets
    - SISP images the central star to study the effects of that star on the habitability of planets and the formation of life on them.
    - TPF, SISP, IRSI/Darwin, and PI together provide complete views of other solar systems

## Current Status

- Included in far-horizon SEC Roadmap (summer 1999)
- Mission concept further developed by
  - C.J. Schrijver (Stanford-Lockheed Institute for Space Research)
  - K.G. Carpenter (LASP - NASA/GSFC)
  - in consultation with informal Concept Development Group
- Presentations of mission concept
  - October, 1999 Cool Stars, Stellar Systems, & the Sun Conference
  - NASA GSFC and HQ on March 6 and March 14, 2000
  - June, 2000 AAS and SPD meetings
- Web site created: **http://hires.gsfc.nasa.gov/~sisp**
- “white paper” written to describe science goals/technology req’ts
- Included in SEC “State of the Theme” report (May, 2000)
- next steps
  - Architecture/Feasibility Studies
  - ground-based Testbed Development Program

## Current Members of the Concept Development Group

| | |
|---|---|
| • NASA-GSFC: | Ken Carpenter (GSFC science lead),<br>Lee Feinberg (GSFC engineering lead),<br>Dick Fisher, Joe Davila |
| • LMMS/ATC: | Carolus Schrijver (LMMS science lead),<br>Domenick Tenerelli (LMMS engineering lead) |
| • U. Vienna: | Klaus Strassmeier |
| • U. Aarhus: | Jörgen Christensen-Dalsgaard |
| • Kiepenheuer Inst.: | Oscar Van der Lühe |
| • Catholic Univ.: | Fred Bruhweiler |
| • U. Colorado: | Alex Brown, Jeff Linsky, Jon Morse |
| • STScI: | Ron Allen |
| • CFA: | Andrea Dupree, Lee Hartmann |
| • Mt.Wilson Obs.: | Sallie Baliunas |
| • SUNY: | Fred Walter |
| • Yale: | Pierre Demarque |

Additional information about the

Stellar Imager

can be found at the following websites:

http://hires.gsfc.nasa.gov/~sisp

and

http://www.lmsal.com/SISP

# Correlation Tracker in Space Solar Telescope

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## ABSTRACT

A correlation tracker (CT) for improving image quality of solar telescope has been built and successfully tested in the lab at Beijing Astronomical Observatory (BAO). This paper will introduce the method of correlation tracker, as well as report on the system composing; the present status of development and preliminary results.

## 1. Introduction

In recent years, many solar physicists have focused their researches on the small-scale structure of solar magnetic fields. So observations with high spatial resolution and sometimes long exposure time are strongly required. An enormous amount of effort is being devoted to the design and construction of new generation solar telescopes (ground-based or space-borne), to reach angular resolutions up to 0.1". However, image motion at focal plane of the telescope caused by random atmospheric turbulence and mechanical vibration severely degrades the resolution of an astronomical telescope. This motion (usually referred to as a first-order aberration) can be compensated for in a portion of the solar image by means of a correlation tracker (CT), which attempts to stabilize the solar image on the post-focus instrumentation.

To correct the image motion, we must detect it accurately. In the case of the solar granulation, solar images features low contrast structure (2%-5% RMS), and exhibits extended, irregular and time-varying shapes. Some detecting technologies for spot objects, for example, centroid and limb measurement, have been unsuitable for this purpose. We adopt the method based on calculating the cross correlation function via FFT inside a small region anywhere on the sun.

Briefly, such systems operate as follows. A two dimensional detector takes solar images at a fast rate. Successive images are compared, using correlation techniques, with a previously stored reference image to determine, in real time, their relative displacements. Each of these shifts is converted into an error signal that moves a fast tilting mirror (agile mirror) thus compensating the wavefront tilt. The reference image is frequently updated to take into consideration the morphological evolution of the tracked structure.

## 2. Image Displacement Detection Algorithm

A reference image R is generated before observations. Successive images called live image L are compared, in real time, with the reference image using correlation algorithm given as following formula:

$$\mathrm{COR}(\Delta x, \Delta y) = \mathrm{IFFT}[\mathrm{FFT}(R)\ \mathrm{FFT}^*(L)]$$

here COR denotes the spatial cross correlation function of reference and live pictures, $\Delta x$, $\Delta y$ are x and y direction displacements respectively. FFT and IFFT denote forward and inverse Fast Fourier Transforms. The asterisk superscript expresses complex conjugation. The correlation function has the maximum where both pictures match optimally. The maximum position indicates the relative shift between reference and live pictures. Obviously, the pixel size of detector determines the displacement precision searched out. For instance, in our Space Solar telescope, a pixel covers 0.33 arcsec. To gain displacements with the sub-pixel accuracy, a quadratic least-square fit algorithm is used in two orthogonal directions with the sub-field of 3 by 3 pixels around the maximum. The high precision shift values in x and y directions are treated as error signals. Finally, the drive signals that are applied to tip-tilt mirror are generated by using the PID servo control algorithm to the error values.

In order to get the displacement precision as high as possible, various corrections including dark current, gain (flat field) and trend should apply to the digitized raw data from CCD camera. Additionally, we find it is helpful to change the image into a binary image using the Laplace Operator. In this way, not only can we improve the accuracy of the algorithm, but also simplifier the hardware FFT realization because the multiplication replaced by XOR operation, which is especially useful in the outer space environment.

## 3. Optical Setup

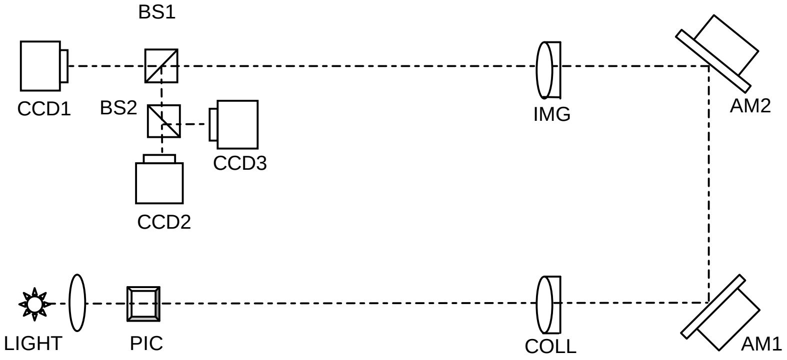


Fig 1. Optical setup of the correlation tracker

Fig 1 shows the drawing of optical setup of the correlation tracker established on Optical Anti-shock Surface Plate. The picture PIC is an artificial target, a solar granulation transparency lit by a lamp and fixed at the focal plane of the collimating lens COLL. Driven by a signal generator, the agile tip-tilt mirror AM1 produces a tilting image. We can conveniently adjust the tilting frequency and amplitude to meet the experimental needs. The agile mirror AM2 in the parallel light path compensates the image motion in real time under the control of correlation processor.

The high-speed CCD camera CCD1 with 64 by 64 pixels placed at the focus of image lens IMG, is the image sensor of the correlation tracker. The beam splitter BS1 in the optical path redirects the beam to the video camera CCD2. The video signal is sent to a TV set (not shown in Fig 1) for viewing images directly. To simulate the situation of long exposure time in solar observation, beam splitter BS2 directs a part of light to camera CCD3. The CCD3 is a frame transfer camera with 768 by 484 pixels. In addition, the saved image files serve to analyze and evaluate tracker performance.

## 4. Electronic Design

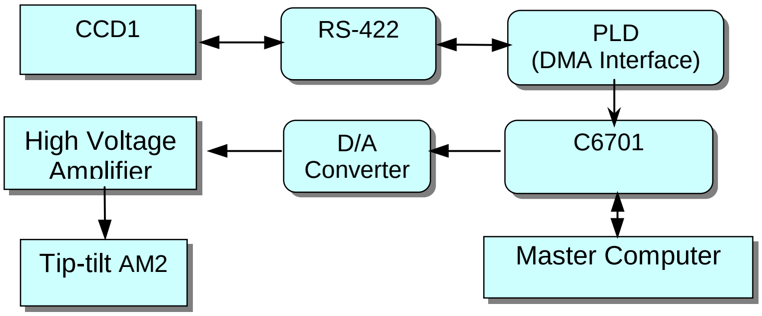


Fig 2: Block diagram of electronic design

- Image detector

A high speed CCD camera, model CA_D1_64T (manufactured by DALSA Inc.) with 16µm physical pixel size and 12bit digital output signal in the RS422 electrical specification, is used as the correlation tracker sensor. The camera works in the binning mode, 2 by 2 physical pixels are binned to one output, so as to reduce the data amount in correlation computation to 32 by 32 pixels (1k data). In this case, the pixel size becomes 32µm, the data rate 5 MHz, the frame readout rate as high as 3250 frame/sec.

- Tip-tilt mirror

A piezoelectric translators unit, model S-340 manufactured by Physic Instrmente (PI), drives the tip-tilt mirror. The full tilting range of the mirror is ±1 mrad and the resolution is 1 µrad. The mechanical resonant frequency is up to 750 Hz, step response time 0.45 ms.

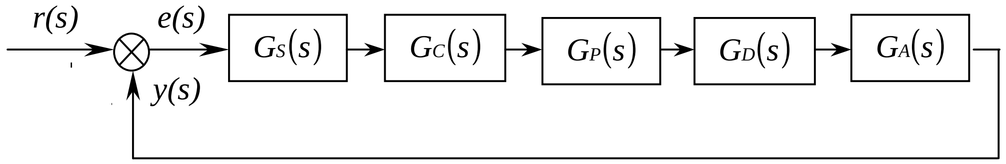
- Correlation processor

A floating-point ADSP-21062 SHARC from ADI (Analog Devices Inc.) acts as correlation processor in our design. It offers 25ns single instruction cycle time at 40 MHz clock, 2 Megabits on-chip SRAM configurable for program and data memory. It takes only 920µs for 32 by 32 points complex FFT.

- Master computer and Serial interface

A commercial Pentium computer acts as the master to control and monitor the tracker. The correlation processor runs on the stand-alone mode. A serial communication is set up between the DSP and the master computer by using a serial interface converter MC145428 (Motorola) that provides RS-232 compatible data port into the DSP's synchronous transmission link and vice versa. Thus the correlation processor can receive kinds of control commands from master to complete following tasks: to initialize system, start or stop tracking, modify the PID arguments and etc. In addition, the correlation processor can also send the error data to master, and then draw the error curve on the screen of master so that we can evaluate the correcting result.

## 5. PID Controller



The transfer function of the system is:

$$G(s)=\frac{y(s)}{e(s)}=\underbrace{K_0\cdot\frac{1-e^{-T_1S}}{T_1s}}_{G_S(s)}\cdot\underbrace{e^{-\tau_0 s}}_{G_C(s)}\cdot\underbrace{\frac{1}{(T_2s+1)(T_3s+1)}}_{G_A(s)}\cdot\underbrace{\frac{1-e^{-Ts}}{s}}_{G_D(S)}\cdot\underbrace{G_P(s)}_{G_P(s)}=G_0(s)\cdot G_P(s)$$

Fig 3. Block diagram for the servo loop of CT

The PID (Proportional, Integral and Derivative) controller from classical control theory is a simple and valid method adopted widely in control system of modern adaptive optics. The block diagram for the servo loop of the CT is shown in figure 3, and the transfer function expressed in S-domain.

The wavefront perturbation r(s) is considered as the demand that needs to be tracked so that the error signal e(s) is minimized. The feedback signal y(s) is the present position of the agile mirror AM2. In the loop, Gs(s) denotes the transfer function of the image sensor CCD1. Gc(s) denotes to total delay time of computation. Ga(s) and Gd(s) show the transfer functions of the agile tip-tilt mirror and the D/A converter respectively. Gp(s) is the transfer function of PID control algorithm. So we can state the system open-loop transfer function G(s) as shown in fig 3.

The system close-loop transfer function is: y(s)/r(s) = G(s)/[1+ G(s)]

Error transfer function is: e(s)/r(s) = 1/[1+ G(s)].

Practically, we may not able to make certain the time constants in formula above for each individual object. The convenient way is to measure the combined frequency response in open loop in the testing optical setup (shown in fig 1) by using a dynamic signal analyzer. Of course, in the measurement the effect of PID control arithmetic should not be included (i.e. the correcting signals are not sent to agile mirror). After getting the open loop frequency response (both gain and phase), the transfer function Go(s) of the system can be derived from it using MATLAB.

As we know, the discrete PID algorithm can be stated as:

$$U(n)=U(n-1)+A_1E(n)+A_2E(n-1)+A_3E(n-2)$$

$$A_1=K_p+K_iT+K_d/T$$

$$A_2=-K_P-2K_d/T$$

$$A_3=K_d/T$$

Where U(n) and U(n-1) are values of the control signal U at sampling interval n and n-1. Similarly, the discrete values of error signal E are shown as E(n), E(n-1) and

E(n-2). The T is sampling cycle. The PID parameters Kp, Ki and Kd can be obtained by using conventional techniques.

Briefly speaking, the PID parameter determination aims at fine tuning coefficients A1, A2 and A3 so that the open-loop transfer function G(s)=Gp(s)Go(s) achieves a stable status (i.e. gain and phase margins of 8db and 45 degree, respectively), and the system close-loop bandwidth (-3db) is as wide as possible. In general, a CT performance depends on its close-loop servo bandwidth. The wider bandwidth, the better tracking results.

## 6. Performance

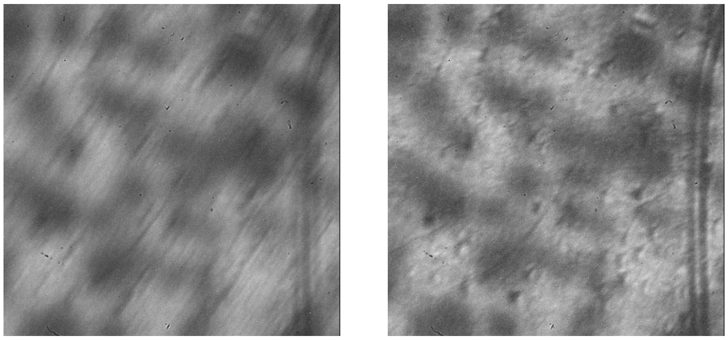


Fig 4. Uncorrected image (left) and corrected image (right)

Figure 4 shows two sample pictures. The left one is an untracked image obtained by CCD3 in an exposure time 0.3 seconds. Adding a 5Hz sinusoidal wave on AM1 to produce the tilting picture, after starting tracking, the picture (right one) has been stabilized obviously. The system servo bandwidth is shown in figure 5. From the frequency response plot, we obtain that the system close-loop bandwidth (-3db, C(f)) has reached at 35Hz and the system error bandwidth (E(f)) is 13Hz.

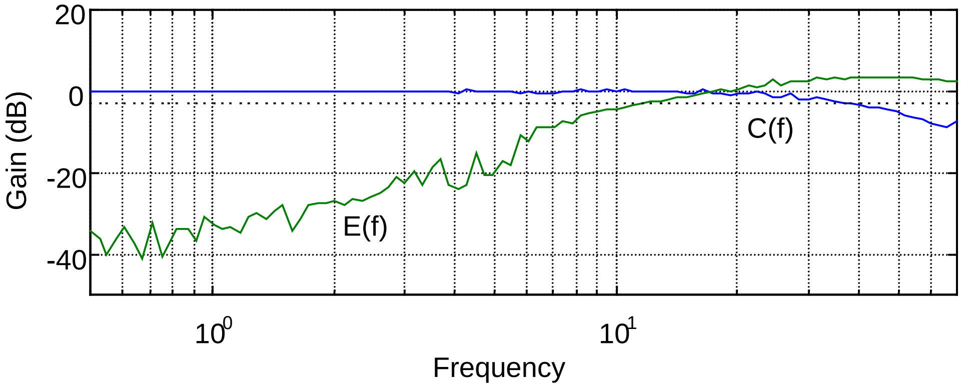


Fig 5. Close-loop frequency response of the system

## 7. Conclusion

In this paper, we have described the basic architecture and preliminary testing results of our CT system built in the lab. The performance of a digital CT is basically restricted by the dynamic response of the components in servo loop. In our CT the main limitation is the time consumption for correlation calculation that takes 2ms so that the sampling rate is limited to 330Hz, though we have a high-speed CCD camera able to reach at more than 3KHz reading rate. To improve this, the considerable ways are to set up a parallel processing DSP system or to choose a much more fast DSP (e.g. TI's TMS320C7x series, which is in process now).

## REFERENCES

Rimmele Th., von der Lühe O., Wiborg P.H., Widener A. L., Dunn R.B., Spence G.: 1991 SPIE, Vol.1542,186

von der Lühe O.: 1983, Astron. Astrophys ., 119, 85

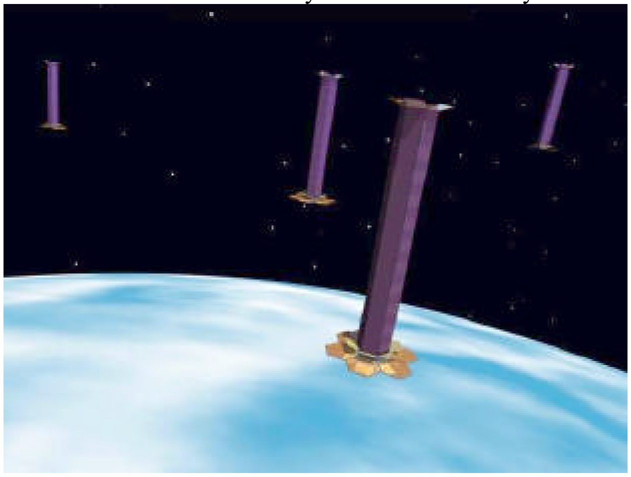
von der Lühe O.: Widener A. L., Rimmele Th., Spence G., Dunn R. B., Wiborg P.: 1989, Astron. Astrophys., 224, 351

# SPHERES

SPHERES (Synchronized Position Hold Engage Re-orient Experimental Satellites) is a spacecraft formation flight testbed developed by the Space Systems Laboratory and Department of Aeronautics and Astronautics at MIT. The objective was to develop a testbed for the validation of metrology, formation flying, and autonomy algorithms to coordinate the motion of multiple satellites in a micro-gravity environment. SPHERES is undergoing 1-g air table testing and flew on NASA's KC-135 in February and March, 2000. Eventually, SPHERES will transition to an International Space Station (ISS) facility for reducing risk in missions of interest to the Air Force and NASA.

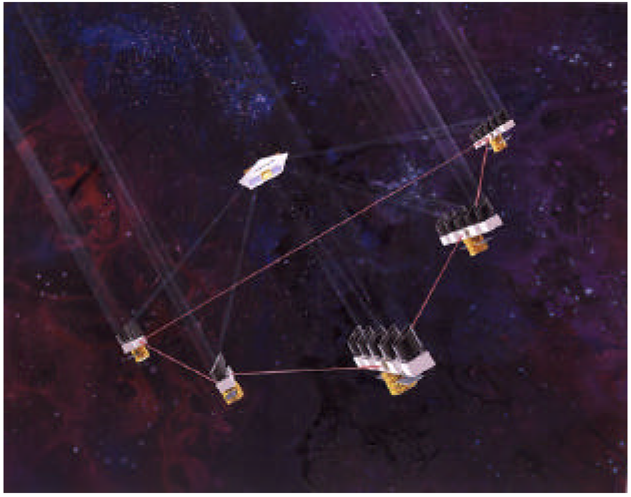
**SPHERES operating in KC-135**

Once on ISS, SPHERES will provide a long-duration, replenishable, and reconfigurable testbed for validating software technologies pertinent to formation flying spacecraft. The micro-gravity of ISS allows all degrees of freedom to be exercised. As illustrated in the figure above, the hands-on nature of the testbed allows direct observations to be made, anomolies to be corrected, consumables to be replenished, and malfunctions to be repaired. As new algorithms are designed, the cycle time from concept to implementation on orbit to analysis of results will be reduced from years to weeks or days.



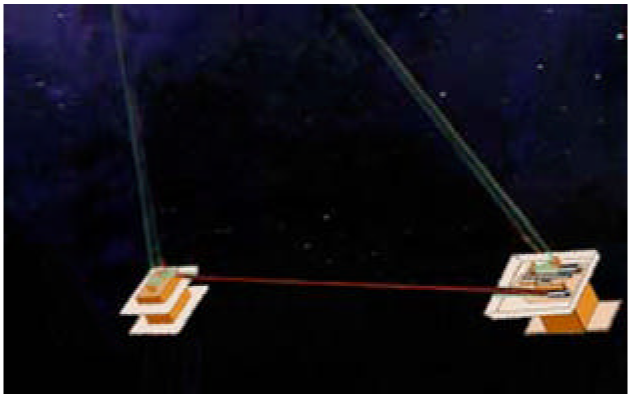
**Air Force Techsat21 Program**

SPHERES will allow testing of (1) relative attitude control and station-keeping between satellites, (2) re-targeting and image plane filling maneuvers, (3) collision avoidance and fuel balancing algorithms, and (4) array geometry estimators necessary for missions such as the Air Force's Techsat 21 and NASA's ST3 and Terrestrial Planet Finder missions. While the dynamics and precision of SPHERES do not necessarily match those required of these missions, it does allow the designers of these missions to validate the algorithm design, initialization, de-bugging, and refinement process.



**NASA's Terrestrial Planet Finder Mission**

The SPHERES testbed consists of three 0.25 meter diameter, 3.0 kilogram, self-contained satellites with on-board propulsion, processing, RF communication and metrology. In addition, the testbed has four metrology transmitters and a laptop which acts as a "ground station" and provides experiment control. On ISS, new algorithms can be uplinked and data downlinked via the Ku-Band system and astronaut laptops.

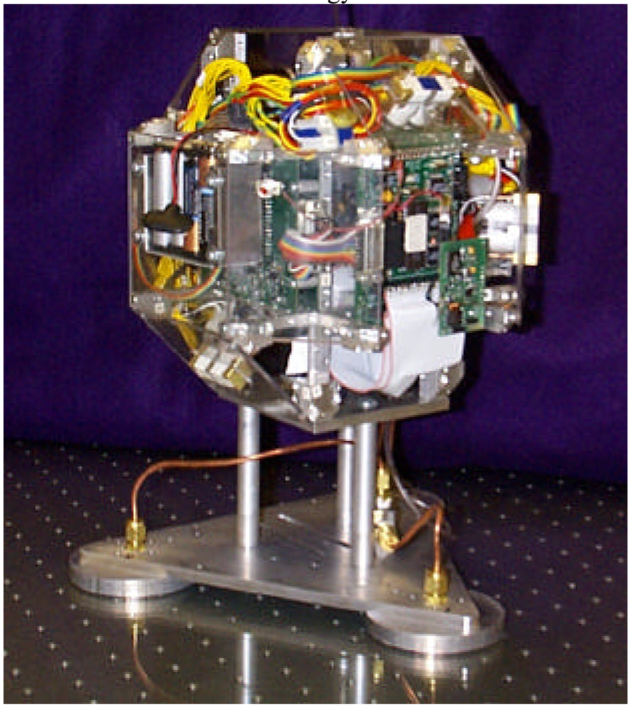


**NASA's ST3 Separated Spacecraft Interferometer**

The following figure shows a SPHERE mounted to a compressed air carriage that allows it to float in two dimensions on a glass surface. The structure is an aluminum frame covered by Lexan panels. The frame allows numerous mounting locations for the various subsystems. The structure was designed using ProEngineer and procured professionally.

The propulsion sub-system consists of twelve solenoid-actuated valves which expel carbon dioxide through micro-machines nozzles. The thrusters are grouped in six opposing pairs to provide attitude and station-keeping control. The propellant is stored in DOT approved steel tanks which hold 74 grams of liquid CO2 at 860 psig. A regulator drops this pressure to 70 psig prior to distribution via a manifold. The tanks are replaceable and provide about 3 minutes of operations.

The metrology sub-system has global and local elements. The global metrology measures the time of flight of 40 kHz ultrasonic pulses emitted by the four metrology transmitters. Infrared transmitters provide precise synchronization pulses. Eight ultrasonic microphones distributed on the surface of the SPHERE are used to derive a total of thirty-two propagation delays used to derive six degrees of freedom. Each SPHERE has a local, internal inertial measuring unit (IMU) consisting of 3 accelerometers and 3 rate gyros.



**SPHERES Prototype on Compressed Air Carriage**

The power and avionics sub-systems consist of replaceable battery packs as well as a TI C40 DSP, a Motorola TattleTale computer, a solenoid firing circuit board, a metrology board, power distribution, a UART internal digital communication board, and two external RF communications circuits. The custom boards were designed using ORCAD and procured from professional board manufacturers. Each SPHERE consumes 12 to 14 Watts under nominal operation.

The software and communication sub-systems are multi-rate and multi-channel, respectively. The realtime software executes a 1.0 kHz interrupt to actuate the thrusters via pulse width and pulse frequency modulation. The control algorithms are updated using a 50 Hz interrupt. Global metrology, inter-SPHERE communication as well as SPHERE-to-laptop communication is updated at one to ten hertz rates. Communication uses a token ring architecture for both the SPHERE-to-laptop as well as the inter-SPHERE communication. SPHERE-to-laptop communication is used to archive measured data and operate the testbed.

**Sample Internal SPHERE Components**

SPHERES was developed through a unique educational experiment where undergraduate aerospace engineering students are exposed to the full lifecycle of an aerospace product through the conception, design, implementation and operation of a world-class facility for validating technologies crucial to the operation of formation flying satellites. Students not only learn about design, teamwork and communication but also interact with potential customers from government and industry, appreciate the constraints of integrating to a carrier, exercise professional computer-aided design tools, and struggle with the iterative process of design improvement and system-wide integration. SPHERES is an innovative blend of research, education and collaboration for furthering the United States' capabilities in space.

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**Student and Staff at Work on SPHERES in NASA's KC-135 Micro-Gravity Aircraft**