Science Applications of the RULLI Camera:
Photon Thrust, General Relativity and the Crab Nebula

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The Remote Ultra-Low Light Imaging (RULLI) Camera, a unique new optical observing system developed at Los Alamos National Laboratory, allows a family of astrophysical and satellite observations that were not feasible in the past. We will describe the results of the analysis of recent observations of the LAGEOS satellite and the opportunities expected for future observations of the nebula created by the Crab pulsar.

The LAGEOS III/LARES experiments have measured the dynamical General Relativistic effects of the rotation of the earth, the Lense-Thirring effect. The major error source is photon thrust and a required knowledge of the orientation of the spin axis of LAGEOS. This information is required for the analysis of the observations to date, and for future observations to obtain more accurate measurements of the Lense-Thirring effect, of the deviations of 1/r^2, and other General Relativistic effects as well as differences between a General Relativity that relate to string theory, The University of Maryland has had the premier program in these measurements. However, at present the rotation of LAGEOS I is too slow for our traditional methods of measurements. The RULLI camera provides the option of extending the measurements. We will discuss the LANL observations of LAGEOS at SOR, the unique software processing methods that allow the high accuracy analysis of the data and the transformation that allows the use of such data to obtain the orientation of the spin axis of the satellite.

In the future, we plan to conduct observations of the nebula close to Crab Pulsar. The rapidly rotating pulsar generates enormous magnetic fields, synchrotron plasma and stellar winds moving at nearly the velocity of light. Since the useful observations to date rely on observations of the beamed emission when it points toward the earth, most of the description of the details of the processes must relay on theoreticians. The RULLI camera will allow useful observations to be conducted that may address properties like the orientation of the rotational and magnetic axes of the pulsar, the temperature, composition electrical state of the plasma and effects of the magnetic field.

1. RULLI Camera

1. 1 Overview

Remote Ultra-Low Light Imaging (*RULLI*) is a sensor system technology enabling breakthroughs in many application arenas. The core of the technology is a single-photon detection system. The *RULLI* sensor system measures, accurately and simultaneously, the position and absolute time of arrival for each detected photon. This opens up many new possibilities for the exploitation of this literally three dimensional data. This Los Alamos technology project is funded by the US Department of Energy.

1.2 Technology

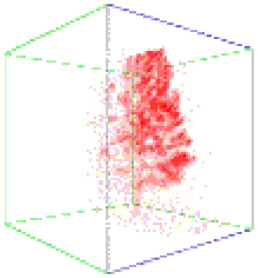
The *RULLI* technology consists of three primary components: the MicroChannel Plate/Crossed Delay Line (*MCP/CDL*) detector, the Pulse Absolute Timing (*PAT*) electronics, and associated photon event construction and data processing techniques.

1.2.1 Sensor: The *MCP/CDL* detector is a hermetically sealed vacuum tube which contains the light sensing material (photocathode) on the backside of the transparent window, a Z-stack of three microchannel plates, and a crossed delay line readout[1]. It offers a high signal read-out rate and good spatial resolution. To date, we have implemented a series of detectors each using a 40 mm diameter MCP (which defines the detector's active area) and an S-20 photocathode which is sensitive in the visible regime.

1.2.2 Electronics: The *PAT* electronics is a fast and accurate timing technology with heritage from the nuclear test program at Los Alamos. The *PAT* system measures the absolute arrival time of individual electrical pulses with an accuracy better than 20 picoseconds.

1.2.3 Data Exploitation: The combination of *MCP/CDL* and *PAT* allows us to acquire single photons with high spatial and time resolution. Spatial resolution at the detector's active surface is projected to be 30 microns. The absolute timing accuracy achieved to date is 200 ps. The projected maximum count rate is about 2 million counts/sec. In addition, we are developing critical customized and optimized data processing techniques, information extraction algorithms, and visualization methods to exploit the data and information generated by the RULLI sensor system[2].

1.3 Field Demonstration of RULLI 3D Imaging Capabilities



1.3.1 Probing Complex 3D Structures: This image displays a 2D projection of the three dimensional distribution of detected photons reflected from a Ponderosa pine. The pine tree was illuminated from a distance with a low-power pulsed laser which was collocated with the stationary sensor. The data is contained in a cubical volume with 13 m on the side. The blue square defines the viewing direction into the data volume. A total of 2.8 million photons are contained in this volume. Detailed complex structure of the tree is clearly revealed by this measurement[3].

The salient features of the RULLI sensor system are as follows: single photon sensitivity, extremely low noise, ambient temperature operation, and non-pixilated contiguous imaging area. Specific advantages of the RULLI system's application to 3D imaging are: large area and simultaneous coverage, no moving parts, and low illumination power requirement.

Los Alamos, in collaboration with other institutions, is actively improving all aspects of the RULLI technology, exploring new single photon sensor concepts, and developing applications that take full advantage of this unique three dimensional sensor capability. For more technical information on *RULLI* and related technologies, contact rulli-poc@lanl.gov

2. Science Applications of the RULLI Camera

We now address two applications of the RULLI camera that involve Astrophysics and General Relativity. The first application addresses measurements in General Relativity and Geophysics. It provides validation of a hypothesis on a method to obtain new data to allow the LAGEOS and future satellites to be productive in the presence of thermal thrust. This is accomplished by a series of observations of the geodetic satellite LAGEOS II conducted using the 3.6 meter telescope at the Starfire Optical Range of the Air Force Research Laboratories. The confirmation of the Pocket Effect has been confirmed and further analysis of this data is proceeding. The second application involves an observation the pulsar in the Crab Nebula. This consists of a series of observations that is being proposed to be conducted on the AEOS telescope using the unique capabilities of the RULLI camera. This will address the highly relativistic behavior of the pulsar and the relation of the pulsar to the surrounding nebula.

2.1Validation of the “Pocket Effect” on LAGEOS II

2.1.1 Background and Objectives

There are two LAser GEOdynamics Satellites (LAGEOS), the first satellite, designated LAGEOS, was built by NASA and launched in 1976 and the second satellite, designated LAGEOS II, was built by the Italian Space Agency (ASI) and launched in 1992. These are the first satellites that were designed exclusively for laser ranging and created in a manner to minimize any error sources that would reduce the ranging accuracy. These satellites consist of an aluminum shell that is populated by 426 cube corner retro reflectors, 422 composed of fused silica for laser ranging with visible wavelengths and four germanium cube corner retro reflectors for ranging with 10 micron laser systems. The former are used in an international program of extremely high precision laser ranging, coordinated by the International Laser Ranging Service (ILRS) [4]. The latter were provided to perform measurements in the infrared for experimental studies of satellite orientation by Leo Sullivan at HayStack and ranging with the HI-CLASS Laser Ranging Systems at AMOS.

Fig. 1 is a photograph of LAGEOS taken during the testing phase at the Goddard Space Flight Center in 1975-1976. This shows retro reflectors mounted in the aluminum shell. The core consists of a brass cylinder to increase the weight to reduce the relative effect of external forces like drag and the thermal forces.

The objectives of the laser ranging program, coordinated by the International Laser Ranging Service (ILRS) consist of geodesy (e. g., establishing a precise grid of reference points to connect the coordinate systems of various local and national regions), geophysics (e.g., detection and measurement of continental drift), earth orientation (e. g., the motion of the spin axis with respect to inertial space) as well as various other scientific goal.

Data is obtained by laser ranging to the satellite, wherein the CCRs reflect the light back to the observing station and the time of flight is recorded. This currently gives the range to millimeters. The data from stations around the globe are then combined to determine an orbit that is accurate to centimeters.

2.1.2 Spin Orientation

During the life of the satellite, the orientation of the spin evolves in a dynamical manner. The torques that cause the change in the spin orientation are primarily due to two effects. The first is the interaction of the spin with the magnetic field of the earth. Due to the spin, electrical currents are generated within the conducting brass core and the aluminum shell. These currents are then acted upon by the earth's magnetic field to produce torques due to the Lorenz forces. The second set of torques are due to the gravitational effect of a "tidal coupling" between the equatorial bulge of the earth and the equatorial bulge of LAGEOS. Thus the dynamical evolution of the spin orientation is dominated by the effects associated with a gyroscope during the first decade after launch. During the second decade it behaves in a manner dominated by the electrometric or Lorenz forces. In the third decade (and into the future) the evolution of the spin is dominated by the forces from the tidal coupling (see Fig. 3).

The solar glints generated by the Fresnel reflection of the sun by the front surface of the retro reflectors has been measured at the University of Maryland over the past two decades. These observations have then been analyzed in order to determine the orientation of the spin axis. [5,6,7]. The typical accuracy of these observations of the spin axis is between 0.5 and 1 degree.

The evolution of the orientation of the spin axis has been studied from a theoretical point of view [Bertotti and Iess, Vorrulick, meris, farenella] in an attempt to predict the orientation. An understanding of the orientation is significant in the analysis of the orbit, as we shall discuss for the thermal thrust effects. However, these early analyses did not include any of the experimental observations of the orientation of the spin axis and very significantly deviated from the actual measured orientation... More recently, Nacho Andres has incorporated the observations into the theoretical model (LOSSAM) in a manner that provides an excellent prediction and interpolation of the spin axis.

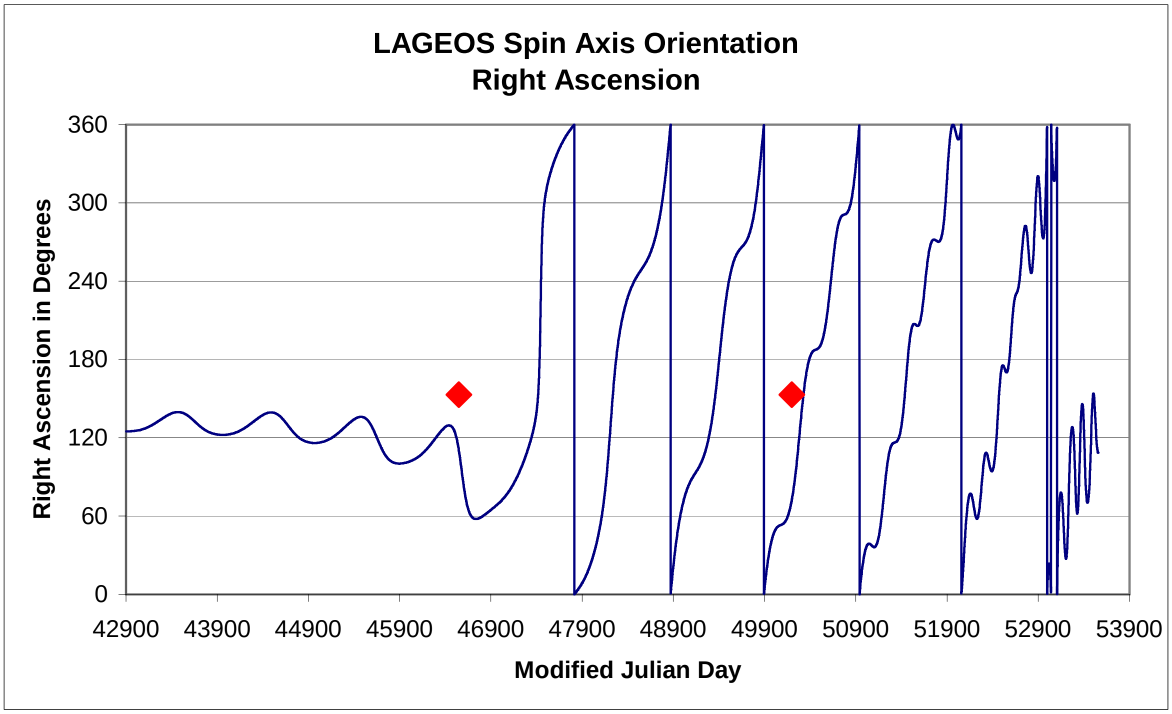


Fig. 2 illustrates the evolution of the Right Ascension of the spin axis as a function of time, from 1976 to 2004, using the measured data as a constraint. The accuracy is a few degrees.

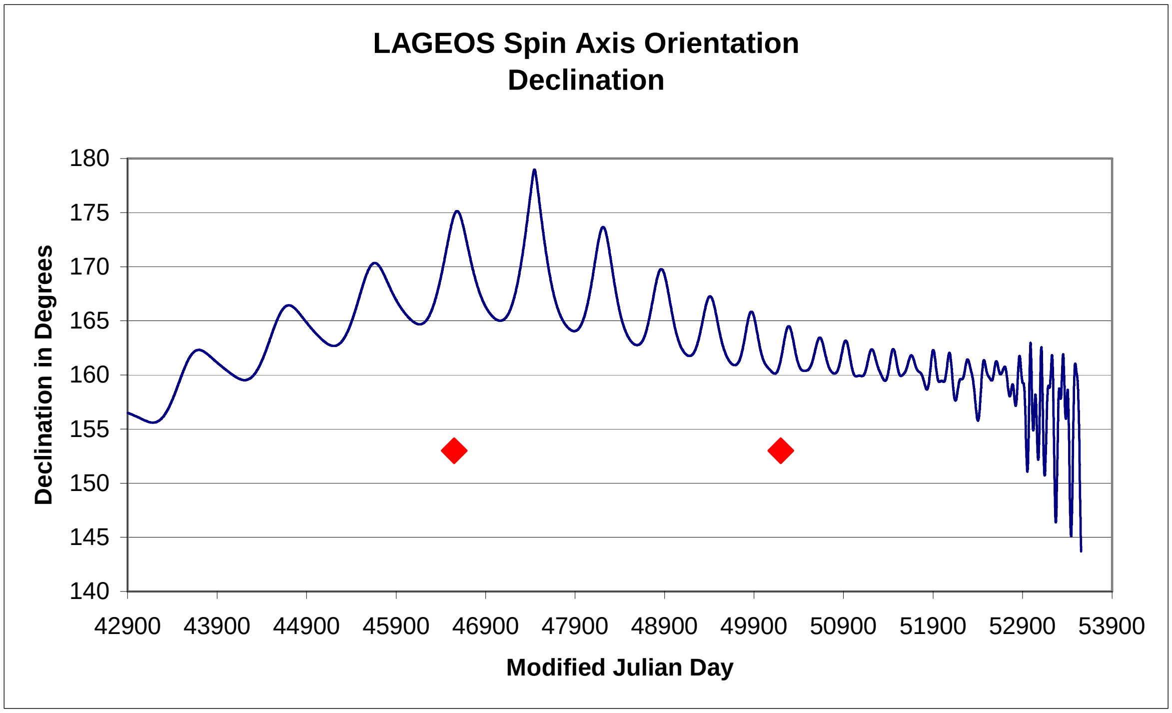


Fig. 3 illustrates the evolution of the Declination of the spin axis as a function of time, from 1976 to 2004, using the measured data as a constraint. The accuracy is a few degrees.

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2.1.3 Photon Thrust or the Thermal Forces

The photon thrust a.k.a. the "thermal forces" a.k.a the Yarkowski forces are non-gravitational forces acting on the satellite. These forces are due the heating of one side of the satellite, by either the sun or the thermal radiation from the earth. The photon thrust is the reaction caused by the emission of an excess number of infrared photons from the warmer side of the satellite. These can alter the orbit of LAGEOS by meters/year. The first application of the Yarkowski concept to LAGEOS was by David Rubincam in his explanation of an anomalous drag force on the satellite [8]. This earth-Yarkowski or Rubincam effect is caused by the heating of the satellite by the infrared emission from the earth. The direction and magnitude of the Rubincam effect depends critically upon the orientation of the spin axis of the satellite. The second Yarkowski force, the "solar Yarkowski effect" is due to the heating of the satellite by the sun. However, this effect cancels, except with the satellite is in the shadow of the earth. It depends critically upon the time constants or rates of cooling of the surface of the satellite while it is in the shadow and when it returns to the sunlight. Again, the magnitude and the orientation of this force is defined by the orientation of the spin axis of the satellite.

2.1.3 Lense-Thirring Effect in General Relativity

All of the tests of General Relativity to date have addressed the static effects. The first dynamical effect to be addressed is the Lense-Thirring effect. This addresses the effect of a rotating mass on the surrounding space time metric. Thus the rotating mass of the earth causes a twist or deviation from closure in the inertial structure of space surrounding the earth. This results in a local "twist" of the inertial systems in which satgellites move. A preliminary measurement of the Lense-Thirring effect has been made using LAGEOS and LAGEOS II [9]. In this approach, the orbits of the LAGEOS satellites moving in the "twisted" metric appear to have an anomalous change in the longitude of the node. The analysis of Ciufolini and Pavlis agrees with the General Relativity prediction within their stated error estimate of 10%. While the effect is small, it means that, to the level that this has been verified near the earth, the inertial frame is not the frame defined by the distance galaxies and stars. The Lense-Thirring effect can also be seen in a gyroscope that is in a spacecraft moving in an orbit about the earth [10]. If the spin axis of the gyroscope started out pointing toward a particular star then on successive orbits, the twist in the local metric causes it to point in a different direction. Again, while the effect is very small, this aspect of the Lense-

Thirring effect will cause the gyroscopes in an inertial platform to drift with respect to the distant galaxies and the stellar sources used on star trackers. This second method of measurement of the Lense-Thirring effect has been addressed by the Gravity Probe B[11] experiment that is expected to provide a more accurate evaluation.

While this effect is very small, as new generations of space missions develop, it is desirable to have measured this effect, rather than to rely on the theoretical predictions of General Relativity.

2.1.4 LARES a.k.a. LAGEOS III Satellites

In order to measure the magnitude of the Lense-Thirring effect and to understand its role in satellite orbits the LAGEOS III experiment was proposed by Ignazio Ciufolini [12]. In this proposal, a satellite similar to LAGEOS would be placed in an orbit with an inclination that is complementary to the inclination of LAGEOS. This configuration of satellites cancels some of the most significant error sources. With the new gravity models available from GRACE and CHAMP other geodetic satellites, the major error source becomes the photon thrust. The vector direction of this force is defined by the vector direction of the rotation axis of the LAGEOS satellite. Thus a knowledge of the magnitude and orientation of the photon thrust is essential, implying a need for the orientation of LAGEOS during the period of the experiment. This new experiment is an Italian effort, with an international collaboration. Currently INFN at Frascati is developing simulation and vacuum chamber facilities for the designand testing of the LARES experiment [13].

2.1.5 Current Challenges in the Measurement of the Orientation of the Spin Axis

For the past decade, a program has been conducted at UM to use telescopes and photometers to observe the solar glints, measure the time interval between the solar glints, and form this data, to deduce the orientation of the spin axis (Currie, Avizonis). However, the analysis method that has been used in the past requires at least a few glints from each band before the solar reflection point moves on to the next band. The energy dissipation due to the internal electrical current has slowed the rotation rate of LAGEOS so much (from 1 rpm to a period of a thousand seconds) that this method of analysis is not feasible. It will soon not be feasible for LAGEOS II. This would mean that in the LAGEOS III experiment where the motion of the nodes of LAGEOS and LAGEOS III would be compared, we would not have available the orientation of the spin of LAGEOS and thus we would have a degraded measurement of the Lense-Thirring effect and the other general relativistic effects. However, a new method of analysis has been proposed by Currie. In this, the low level diffuse/secular reflection would be modulated as the image of the sun moved from the reflecting aluminum surface to the pocket in which the cube corner retro-reflectors are located. This would allow a modulation of the reflectivity and would not be as sensitive to angular constraints which govern the solar glints. Thus we will have an order of magnitude more “modulations”. This in turn would allow the determination of the orientation for a satellite that is rotating too slowly for the solar glint to be used. However, prior to the observations using the RULLI camera, there have been no measurements with the combination of the proper sensitivity and the proper time resoltiuon to determine if this effect can indeed by used in the manner proposed by Currie.

3. RULLI Observations

The RULLI camera was used to observe LAGEOS II on the 3.6 meter telescope at the Starfire Optical Range in 2004. At this time, LAGEOS II was still rotating fast enough so there are multiple solar glints per band. In this manner, we can analyze the data by the existing Solar Glint method, and also evaluate the possibility of using the Pocket Effect to extend the time period during which we can determine the orientation. Thus we have the opportunity to then for the orientation and analyze the potential of the Pocket Effect. The photometric results obtained from one of the observation sequences is shown in Figure 5. The time interval is 600 seconds. The upper curve is a linear presentation, normalized in order to cover the full range of the photometry. This illustrates the “normal” set of sun glints that would be used to determine the orientation of the spin. In order to remove the long term drift effects, this has been median subtracted. It is sampled at a 20 millisecond rate. The lower curve has been amplified to better show the much weaker variation in the signal due to the Pocket Effect. This data has been both median subtracted and median smoothed. Thus we see that there are only a few solar glints for LAGEOS II. LAGEOS is much slower. However, there are many Pocket Effect peaks, so we may expect that they will be usable for obtaining the orientation of the spin axis. The Pocket Effect peaks have been tested for the accuracy of the timing and the precision is good and the physics seems reasonable. There are some anomalies for the Solar Glints, and we are starting a project to make laboratory measurements as to the reflecting surfaces and the source of the anomalous Solar Glints.

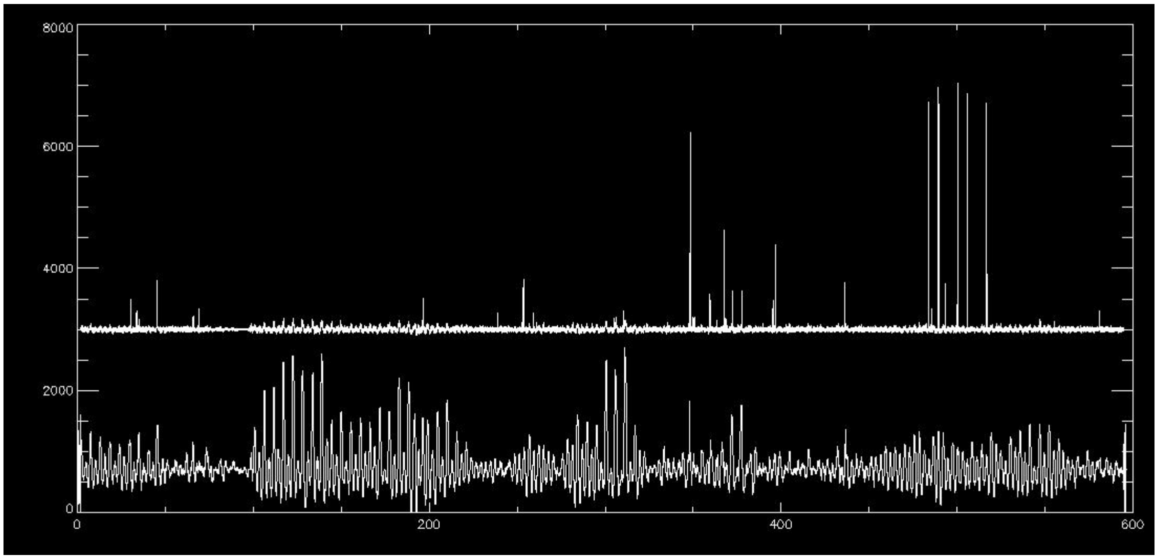

Fig. 4 – This illustrates the solar illumination and solar glints as detected by the RULLI Camera. This is a 600 second record. The upper curve is the median subracted binned intensity, normalized to the peak value of the solar glints. The lower curve is the median smoothed, median subtracted binned intensity normalized to illustrate the Pocket Effect.

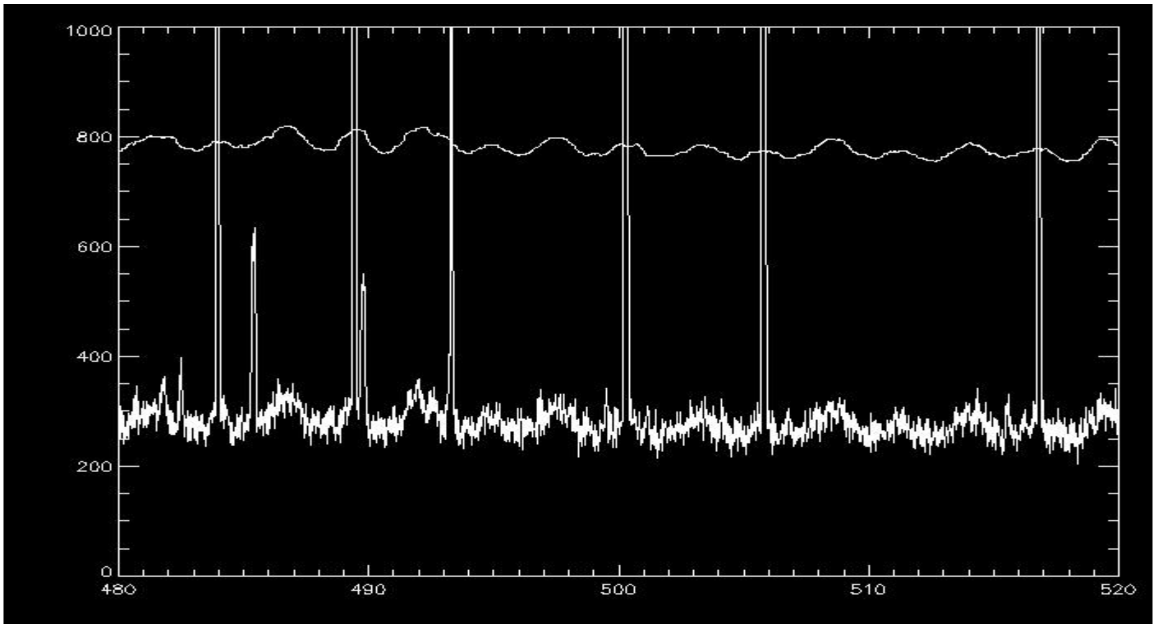

Fig. 5 – This illustrates the solar illumination and solar glints as detected by the RULLI Camera. This is an expanded portioin of the data shown in in Fig. 4. It covers the interval from 480 seconds to 520 seconds.

The latter filtering procedure reduces the photon noise. The RULLI camera allows both very high sensitivity and very good time resolution. The latter allows us to inspect each pulse. In the case of the Solar Glints, each of these Solar Gints represents the scan of a few arc second beam across the disk of the sun. Thus we can see the limb darkening in Fig. 6. Similar results with less time resolution appear in the thesis by Avizonis[7].

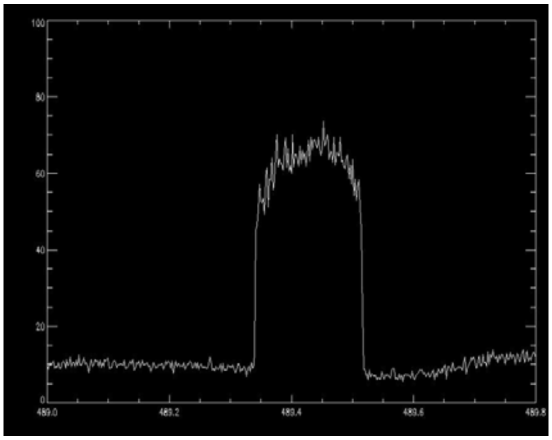

Fig. 6 This illustrates one of the Solar Glints with a binning of 2 milliseconds. The width 0f the Glint is about 150 milliseconds. The limb-darking is clearly shown.

The structure of the Pocket Effect signal is determined by the Point Spread Function (PSF) of the reflection of the sun on the surface of the aluminum. This has both a specular portion and a diffuse portion that extends over more than one band of cube corner retro-reflector. This is important, since the glints are somewhat anomalous. We will be looking at and engineering model of LAGEOS to evaluate these effects.

Due to the high time resolution of the RULLI camera, we can both see that the Pocket Effect is quite feasible. We also see some anomalies in the Solar Glints. These will be addressed with a program in which an engineering model of LAGEOS will be used in a series of ground-based measurements to determine the source of the anomalous glints.

4. Observations of the Crab Nebula

We now consider a possible astrophysical application of the RULLI camera. In this we make use of the combination of the imaging aspect and the excellent time resolution. At the center of the Crab Nebula is a pulsar that is rotating at 30 times a second. As this beam sweeps about, it excites the surrounding medium. In addition, the rotating magnetic field and the excitation produce a strong synchron radiation field. Time sequence observations have previous shown extremely interesting phenomena, but these were at time intervals of weeks, and microseconds. At the RULLI time constants, one can consider localized clumps of material. As the beam sweeps over such a clump, it will excite the atoms of the clumps. They will then rapidly decay yielding a burst. The existence of such clump (i.e., less than a light millisecond across) is not known, but clumps of a variety of sizes that are as small as can be resolved and exists as unresolved elements. These have been seen in the Crab and in planetary nebula. Due to the receptive nature of the Crab pulsar, we can collect data for a long time and then reconstruct the behavior.

One might ask if there is material that is close to the pulsar. The following are observations

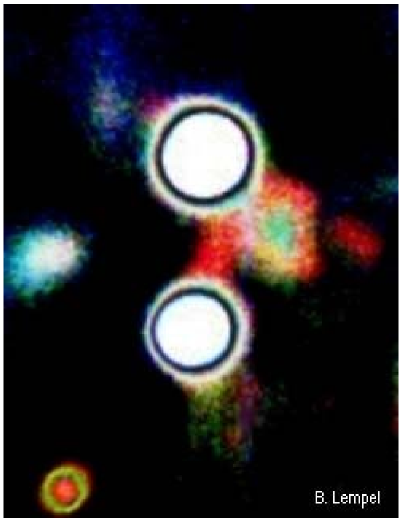

Fig. 6 VLT Observation of the Pulsar, with is the lower star. Notice the "bridge" from the Pulsar toward the upper star.

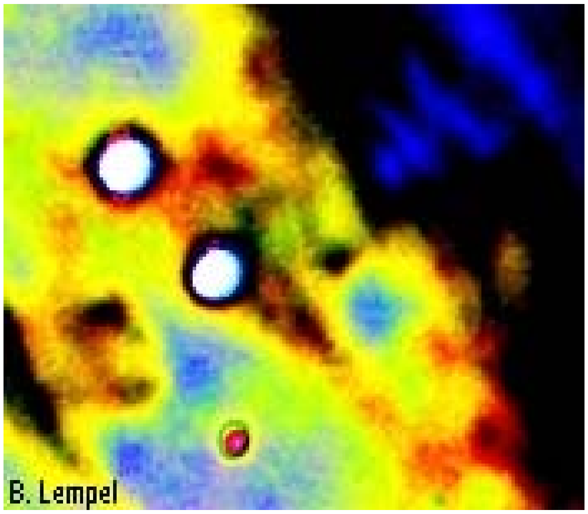

Fig. 7 HST observation of the Crab Pulsar, which is the centered star. Notice the disk-like extensiton that is toward the upper star and even stronger away from the upper star.

While the SNR for the nebula immediately surrounding the pulsar yields reasonable observation times, the expected existence, brightness and contrast of the clumps still needs to be addressed and simulated. However, there would be enormous scientific value if such observations could be accomplished.

5. Conclusions

The excellent time resolution RULLI camera and the sensitivity available with the use of the 3.6-meter telescope has allowed the validation of the Pocket Effect for extending the useful lifetime of the LAGEOS satellites.

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