

# **Transmitter Point-Ahead using Dual Risley Prisms: Theory and Experiment**

**John Degnan<sup>1</sup>, Jan McGarry<sup>2</sup>, Thomas Zagwodzki<sup>2</sup>,  
Thomas Varghese<sup>3</sup>**

**<sup>1</sup>Sigma Space Corporation, <sup>2</sup>NASA/GSFC, <sup>3</sup>Cybioms**

**16<sup>th</sup> International Workshop on Laser Ranging**

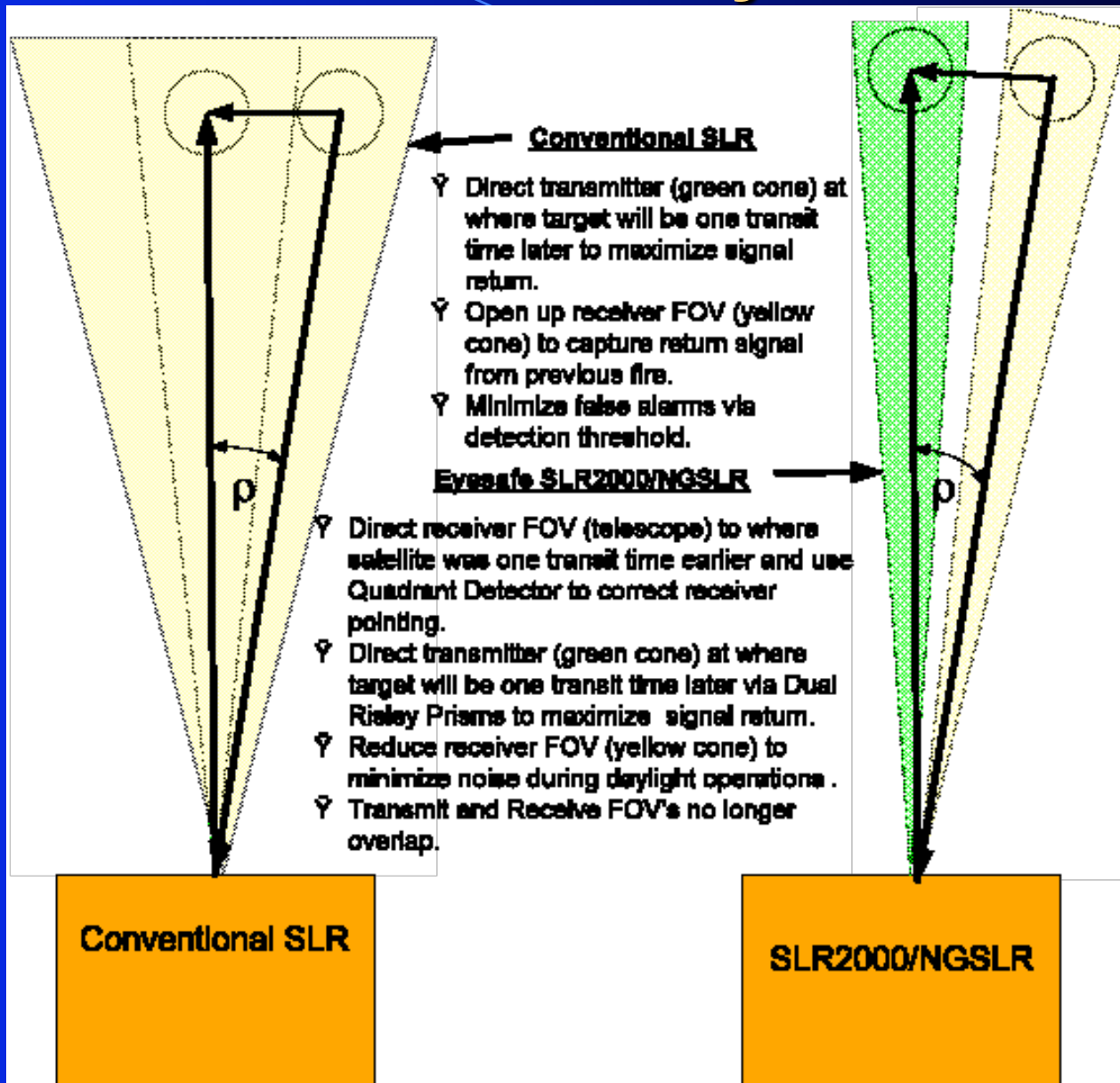
**Poznan, Poland**

**October 13-17, 2008**

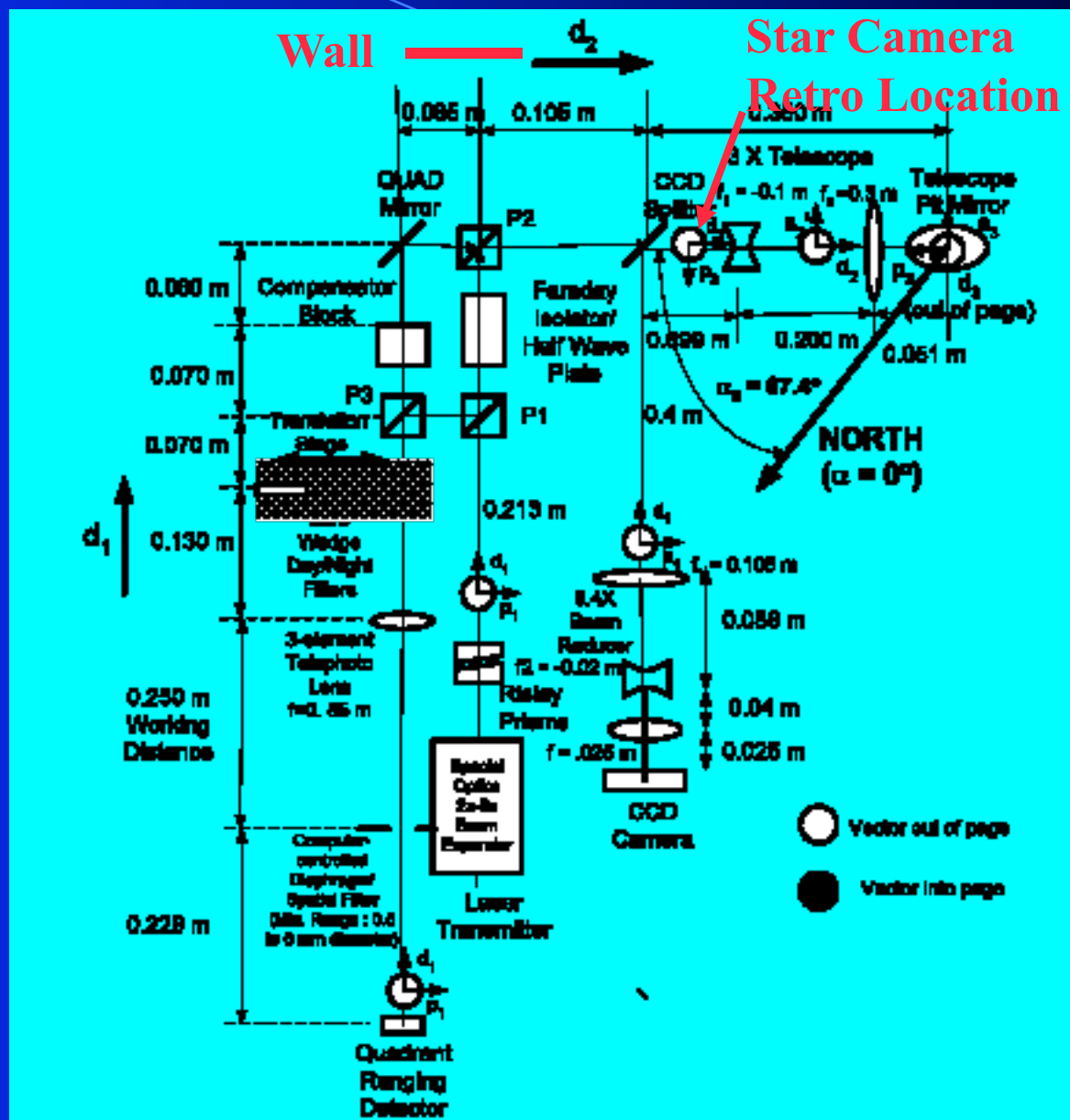
# Why Transmitter Point-Ahead?

- Unlike conventional SLR, the eyesafe SLR2000/NGSLR system operates with transmitted pulse energies three orders of magnitude smaller ( $\sim 60 \mu\text{J}$ ) and is designed to be autonomous (no operator).
- Automated pointing of the telescope/receiver is accomplished using a photon-counting quadrant MCP/PMT detector which seeks a uniform distribution of counts among the quadrants.
- In order to concentrate more laser energy on high satellites, the transmit beam divergence is narrowed by a computer-controlled beam expander in the transmit path.
- To prevent saturation of the MCP/PMT detector during daylight operations, the receiver FOV must be restricted to roughly  $\pm 5$  arcsec, which is smaller than the largest anticipated point-ahead angle of 11 arcseconds.
- Since the transmit and receive FOV's no longer overlap as in conventional SLR systems, transmitter point ahead (i.e. separate boresighting of the transmitter and receiver) is required.

# Conventional SLR vs Eyesafe NGSLR



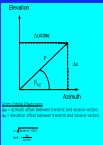
# NGSLR Transceiver Block Diagram



# Point-Ahead Procedures

- Point-ahead angles, expressed in the azimuth and elevation axes of the telescope, are obtained from the orbital prediction program.
- In determining the appropriate Risley rotation angles, we must properly take into account the complex and time dependent coordinate transformations imposed by the various optical components in the transmit path and the axis rotations of the Coude mount as the pulse travels from the Risleys to the telescope exit aperture.
- Finally, we must account for any angular biases between the two servo “home” positions and the actual direction of deflection by the prisms.

# Definition of $\beta_{AE}$ and $\rho$



$$\rho = \sqrt{(\Delta \alpha \cos \epsilon)^2 + (\Delta \epsilon)^2}$$

$$\tan \beta_{AE} = \frac{\Delta \epsilon}{\Delta \alpha \cos \epsilon}$$

# Definition of Coude $\theta$ -Parameter

- The Coude  $\theta$ -Parameter takes into account the axis rotations introduced by the Coude mount and is given by:

$$\theta = \alpha - \alpha_0 - \varepsilon + \frac{\pi}{2} = \alpha - \varepsilon + 22.5^\circ$$

where

$\alpha$  = satellite azimuth

$\varepsilon$  = satellite elevation

$\alpha_0$  = system specific azimuthal bias =  $67.5^\circ$  for NGSLR

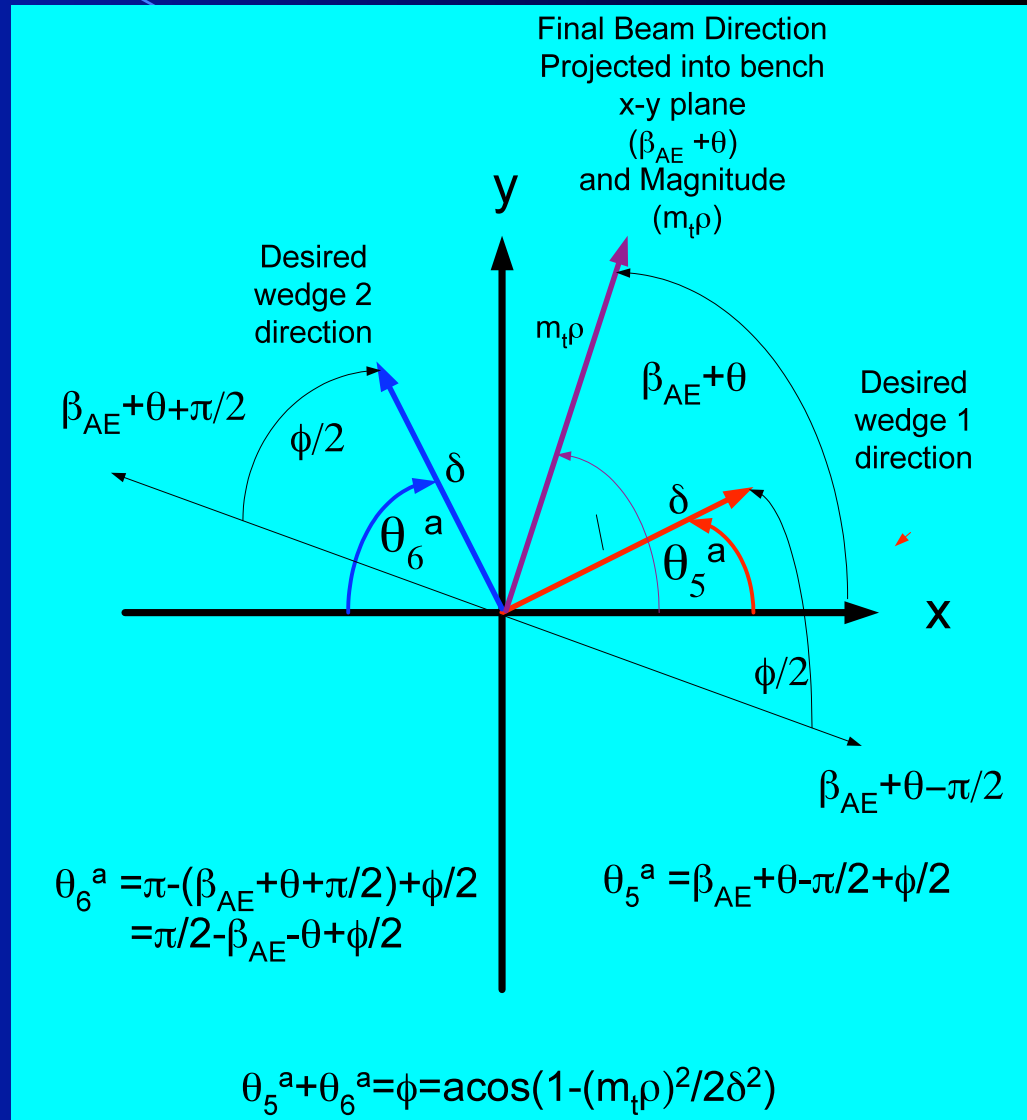
# Bias Free Risley Command Angles

- Deflection by an individual prism is in the direction of the thickest part of the wedge.
- The magnitude of the deflection is given by

$$\delta = (n - 1)w = 15.6 \text{ arc min}$$

where  $n = 1.52$  is the refractive index and  $w = 30$  arcmin is the wedge angle

- The final deflection is the vector sum of the two individual wedge deflections as in the figure. It makes an angle  $\beta_{AE} + \theta$  with the positive x-axis of the bench. The magnitude is equal to  $m_t \rho$  where  $m_t$  is the post-Risley transmitter magnification and  $\rho$  is the point-ahead angle magnitude.





# Physical Explanation

First term ( $\pi/2$ ): Makes the two wedges antiparallel, cancelling out the deflection ( $\rho = 0$ ), with the individual deflections lying along the bench y-axis.

Second term ( $\theta$ ): Rotates the bench x-y axes into the instantaneous azimuth-elevation (az-el) axes at the telescope.

Third term ( $\beta_{AE}$ ): Rotates the deflection direction to the proper value in the telescope az-el reference system ( $\rho$  still equal to zero).

Fourth Term ( $\phi/2$ ): Provides the final magnitude for  $\rho$ , properly accounting for the post-Risley beam magnification,  $m_t$ , and the wedge deflection angle,  $\delta$ .

$$\theta_5^c = +\frac{\pi}{2} - \theta - \beta_{AE} + \frac{\phi}{2}$$

$$\theta_6^c = -\frac{\pi}{2} + \theta + \beta_{AE} + \frac{\phi}{2}$$

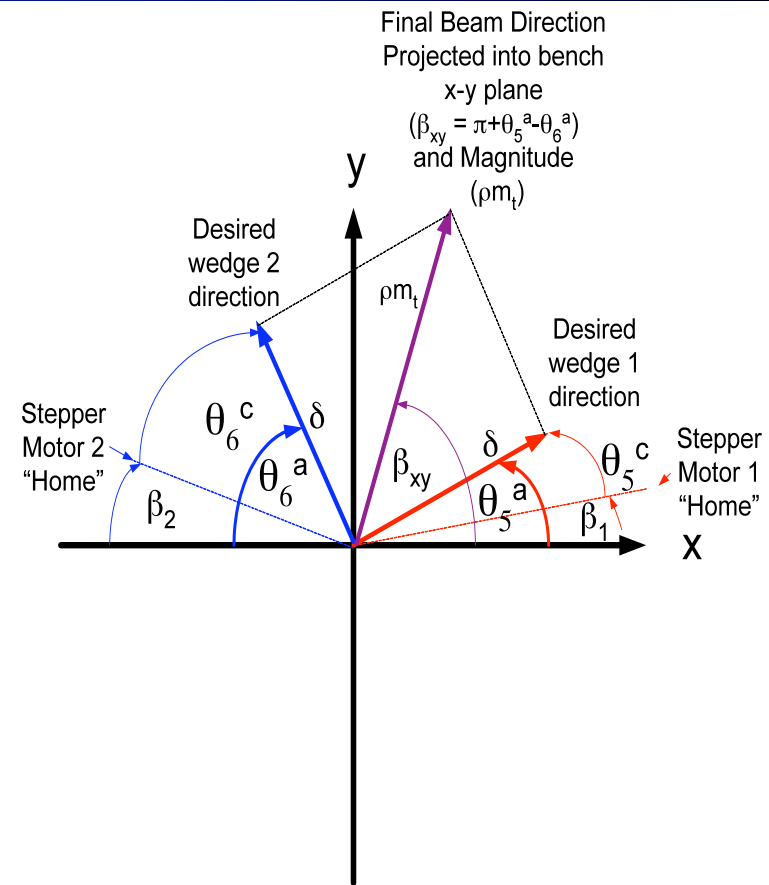
$$\phi = a \cos \left[ 1 - \frac{(m_t \rho)^2}{2\delta^2} \right]$$

# Risley Command Angles with Biases

- The home positions of the servos may be displaced in angle (positive or negative) relative to the bench x-axis leading to “rotational biases” as in the figure.
- The command angles,  $\theta_5^c$  and  $\theta_6^c$ , are therefore adjusted from the actual values,  $\theta_5^a$  and  $\theta_6^a$ , according to

$$\theta_5^c = \theta_5^a - \beta_1$$

$$\theta_6^c = \theta_6^a - \beta_2$$



$\rho$  = satellite point-ahead angle

$m_t$  = total transmitter magnification beyond Risleys

$\theta_5^a$  = actual ccw direction of wedge 1 deflection relative to positive bench x-axis

$\theta_6^a$  = actual cw direction of wedge 2 deflection relative to negative bench x-axis

$\beta_1$  = bias angle between positive bench x-axis and servo 1 home position

$\beta_2$  = bias angle between negative bench x-axis and servo 2 home position

$\theta_5^c = \theta_5^a - \beta_1$  = commanded direction of wedge 1 deflection

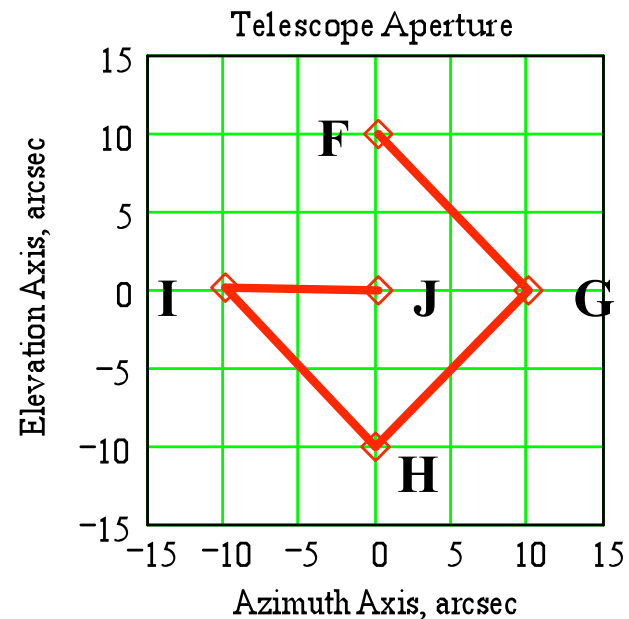
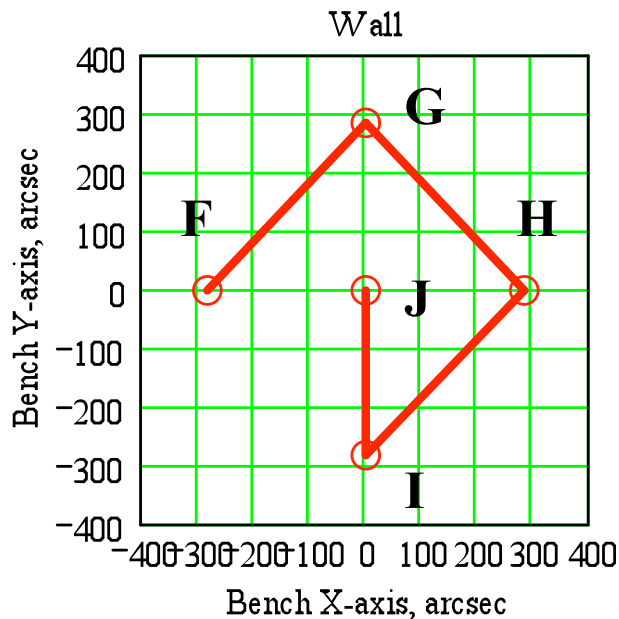
$\theta_6^c = \theta_6^a - \beta_2$  = commanded direction of wedge 2 deflection

$\beta_{xy}$  = actual angle of deflection relative to positive bench x-axis.

# Experimental Validation

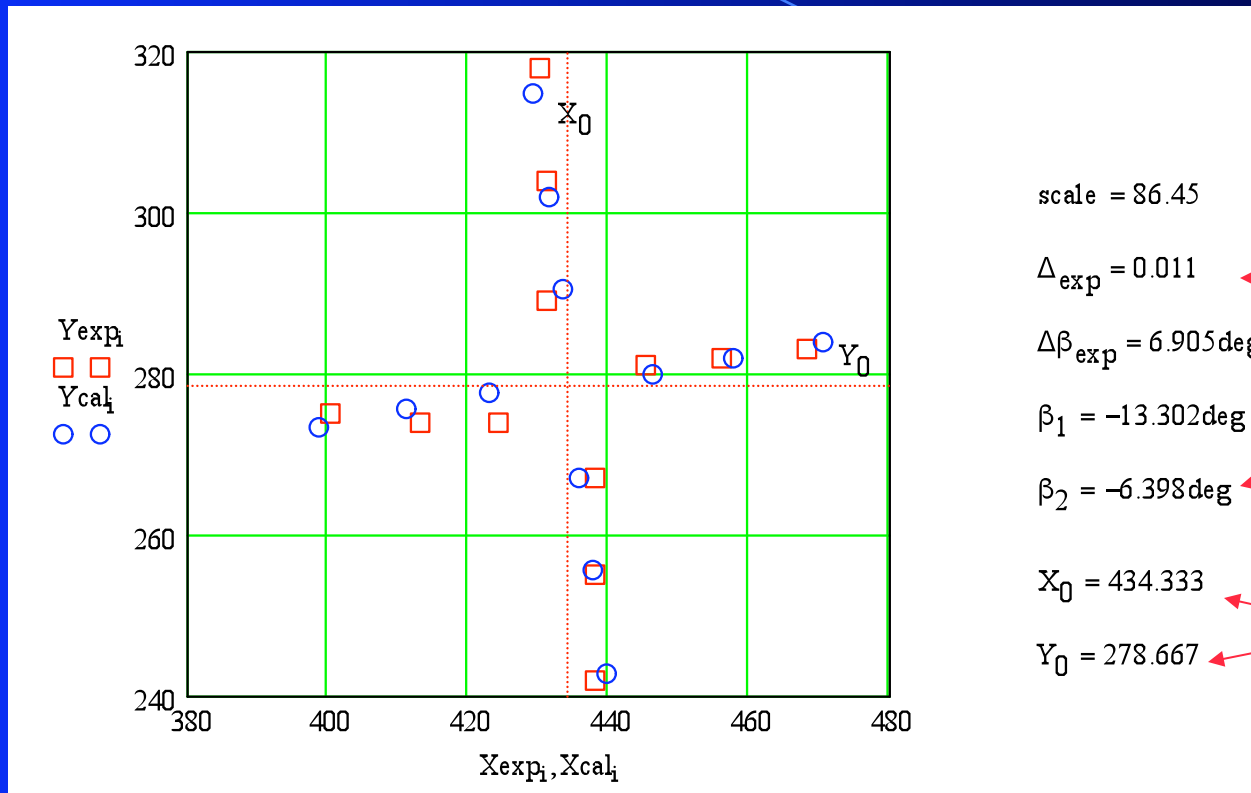
- The deflected beam from the Risleys was projected onto the wall and measured for several values of  $\rho$  and  $\beta_{AE}$ .
- The deflected beam was also viewed at the telescope exit window.
- In a separate set of experiments, a retroreflector placed in the transmit path before the 3-power beam expander reflected the laser beam into the star camera which provided arcsecond quality angular measurements.
- These experiments were used to:
  - Check/determine the validity of servo controls and algorithms
  - Measure the rotational bias angles
  - Estimate the difference between the two wedge angles.

# Experimental Validation at Wall and Telescope Aperture



These experiments validate the predicted orientation and spread of the spots on the wall and at the telescope aperture. In this particular experiment,  $\rho$  was constant at 10 arcsec except for point J ( $\rho=0$ ) and  $\beta_{AE}$  took on values 0,90,180, and 270°. As expected, the telescope aperture pattern is rotated by  $\theta = 90^\circ$  with respect to the wall pattern and the angular deviations are smaller by a factor  $m_t = 28.21$ .

# Star Camera Experiments



scale = 86.45

$\Delta_{exp} = 0.011$

$\Delta\beta_{exp} = 6.905\text{deg}$

$\beta_1 = -13.302\text{deg}$

$\beta_2 = -6.398\text{deg}$

$X_0 = 434.333$

$Y_0 = 278.667$

Wedge Angle  
Difference

Biases

Star Camera  
Origin

- In the above plot, the abscissa and ordinate values correspond to star camera pixel numbers.
- Each pixel corresponds to about 0.49 arcsec of movement.
- Each individual red square corresponds to the observed location of the retroreflected transmitter spot in the star camera image plane for different point-ahead angles and orientations.
- Each blue diamond corresponds to the position predicted by theory.
- This experiment provided extremely high angular resolution and provided the numerical values for the rotational biases,  $\beta_1$  and  $\beta_2$ .
- It also indicated that the wedge angles differed by about 1.1%.

# Summary

- The development of the point-ahead algorithms was approached through both theoretical ray analyses and experiment until we achieved agreement.
- We are now prepared to implement the automated receiver pointing correction and transmitter point-ahead features needed for reliable daylight ranging.
- During the star camera experimentation, we found that the two prisms have slightly different wedge angles (1.1%) so that zero deflection can never be achieved. Ignoring this difference produces a maximum transmitter pointing error of about 1.5 arcsec for small  $\rho$ . For larger  $\rho$ , the errors are typically sub-arcsecond.
- Similar transmitter point-ahead systems and algorithms will be required for future interplanetary laser transponder and communications systems where  $\rho$  can take on values of several tens of arcseconds.