Theory of Operation
for ASI Linear Encoders

The ASI Linear Encoder has many features made possible by its optical design. It is based on some interesting properties associated with point source diffraction by a grating. The most useful properties occur on a plane which is parallel to the grating and which also contains the point source.

Amazingly, everywhere on this plane we get straight, uniform interference fringes as if we were using two perfectly collimated beams!

A laser diode, or an imaged spot can conveniently approximate the point source from a laser. **Figure A** below shows light from a near point source whose central ray forms an angle of 30 degrees with the normal of the chrome-on-glass grating.

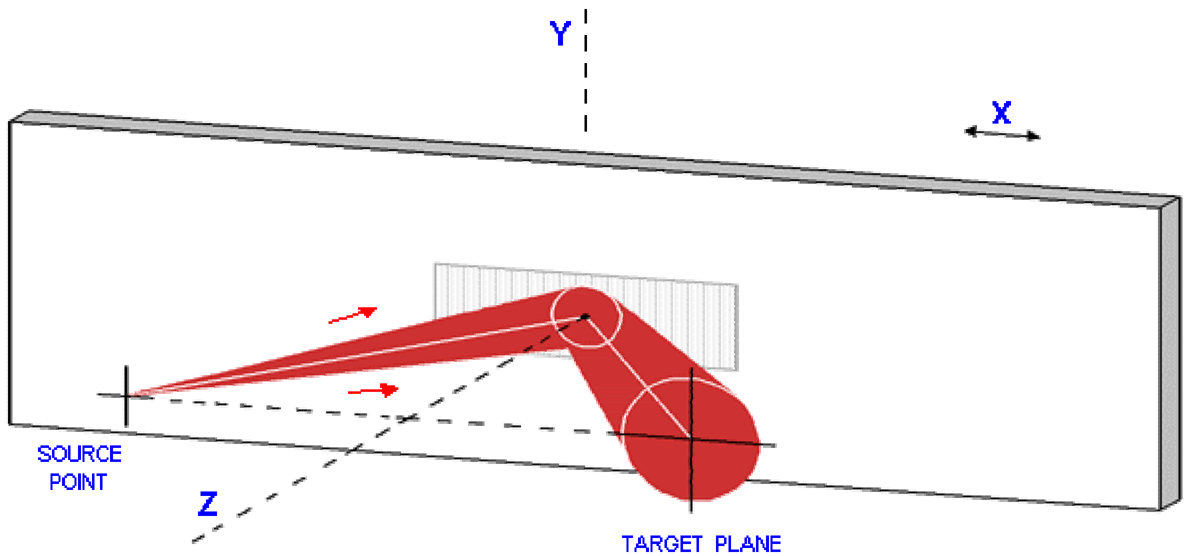

Figure A. Geometry for point source diffraction

Most of the light simply reflects off the grating but some is diffracted into different orders. The rays from each diffracted order also fan out, and overlap the reflected beam. If we look at a particular point on the target plane, light can arrive there from a multitude of paths. First, from direct reflection, and then from each of the positively and negatively diffracted orders. We can see this in Figure B below. Here too, the central ray has a 30 degree angle of incidence. Plus and minus odd diffraction orders up to 9 are shown. This depiction is for an 8 micron scale and 800 nm light.

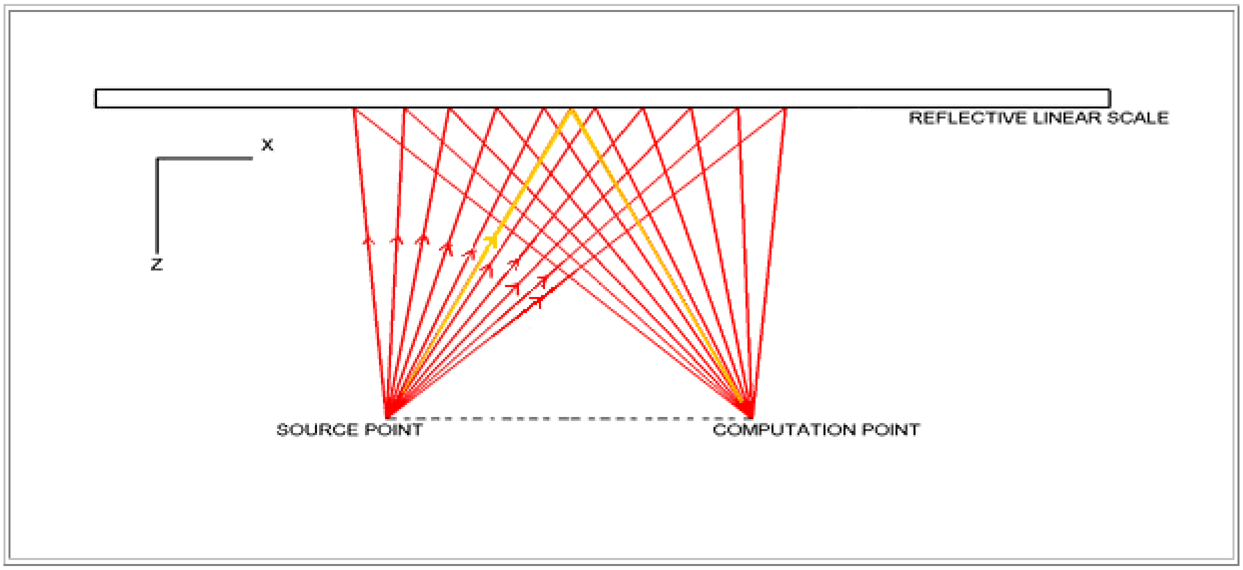

Figure B. Beam paths taken by diffraction orders in going from source point back to special plane.

Notice, say for the first order, that light which leaves the point source at definite angle to the right of the beam centerline will strike a certain point on the scale to the right of center, and then be negatively diffracted at such an angle that it strikes our target point. Likewise, a ray leaves the point source at a definite angle left of center, strikes a point on the scale left of center, and is then positively diffracted at an angle which causes it too to intersect our target point. The intersection of these rays and the directly reflected beam results in a complex interference pattern.

Figure C shows such an intensity pattern in a 16 by 16 micron region in the center of this target plane. The pattern shows some quite bright areas which align themselves with the central beam direction, 30 degrees. This pattern changes as the scale is displaced in **x.**

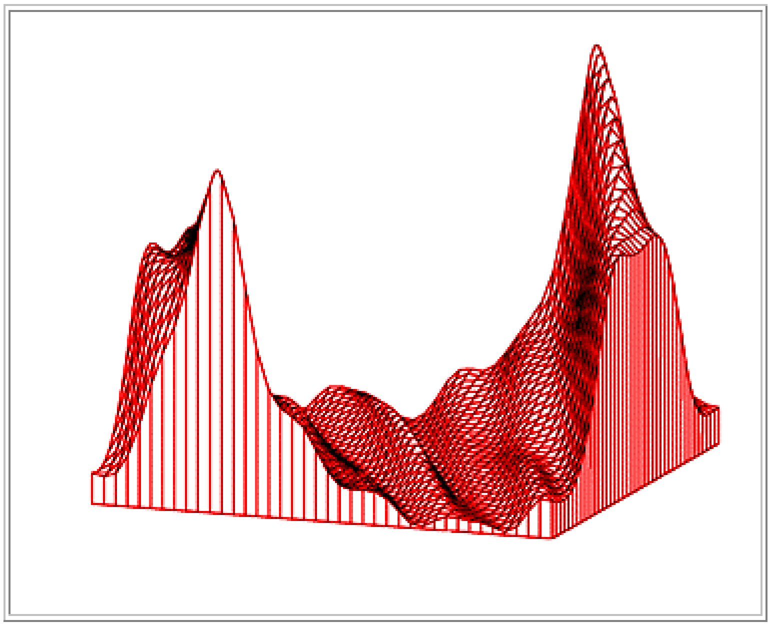

Figure C. Intensity profile at the center of Target Plane

It should be noted that the predominate pattern seen in **Figure C**, is created from the interference of the zero and first order beams. This pattern cycles every 16 microns in **x**, and repeats every 8 microns as the linear scale is displaced. However, its amplitude and phase varies across the plane. In fact, there are regions where it doesn't exist.

Let's go back to the interference effects of just two beams, one diffracted negatively and one positively of the same numeric order. This is depicted in **Figure D** below for n = +/-1. **At any point on our target plane the distance traveled by each beam from source to scale to target plane is identical.** This means that wavelength variations of the source will not affect their phase difference. It also means that from a design standpoint we may orient our central input angle at any angle which is most convenient.

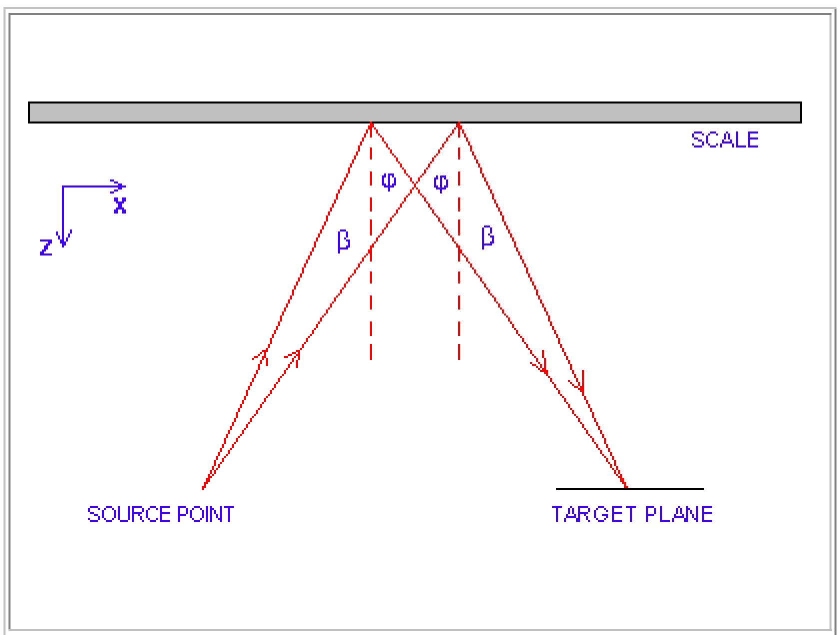

Figure D. Interference of +n and -n diffracted orders

The incident and diffracted angles are given by the diffraction equation:

$$\sin \varphi \ - \ \sin \beta \ = \ \frac{|n|\lambda}{s}$$

The intensity produced from these interfering beams is purely sinusoidal everywhere on the plane. **Figure E** shows these fringes in the same 16 by 16 micron region. The period is "s" divided by "n", where "s" is the grating spacing and "n" is the order. Further, if the scale is translated along **x** by s/2n, the position of this sinusoid has moved by one period. So if we move an 8 micron grating by 4 microns, our 8 micron interference pattern has moved by one fringe. The straightness along **y** and uniformity along **x** of these fringes only exists on this plane.

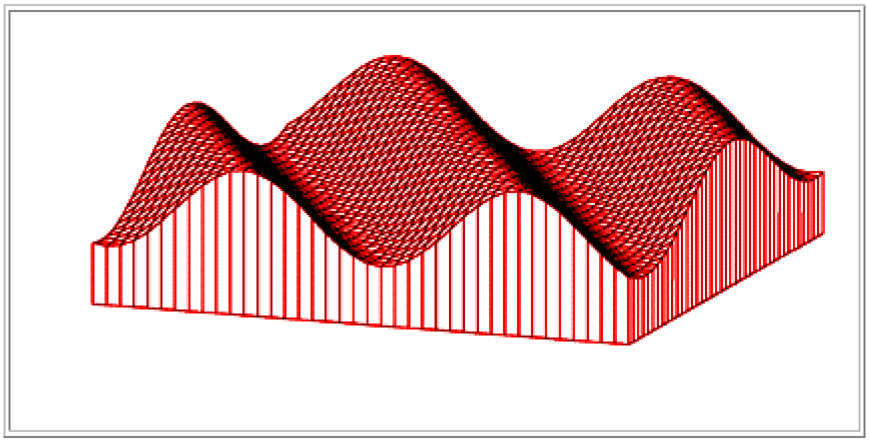

Figure E. Intensity profile of first order beams only

Another very important fact is that if we move the scale closer or further from the point source, i.e., along its normal in the **z** direction as depicted in **Figure A, B,** and **Figure D**, the fringe pattern at the target plane doesn't change its spacing or phase. *It doesn't change at all.* This scale motion will cause the light which interferes at our target point to have come from different source rays, but they will have diffracted **from exactly the same two locations** on the scale as before. This means that our measurement system will not be influenced by **z**-axis translations. Also, since the detected beam is smaller than the length of the scale lines, **y**-axis translations are likewise ignored.

We can sense scale motion using our desired interference pattern by placing a Ronchi grating with the appropriate period right at our target plane. This will "beat" out the pattern we want in the form of a Moire' fringe pattern. Fringe patterns involving other beams yield spatial frequencies which are of no consequence. This too, is quite an important aspect.

Our electro-optical system is then composed of very few parts: a laser diode, Ronchi grating and photo-detection. We do not require any beam steering or refractive elements.

As stated, the fringe uniformity over our special plane means that we may direct our source towards the linear scale at any angle we choose.   To maximize the tolerance to yaw rotations we have chosen an angle of 20 degrees in the **yz** plane for the encoders. This is shown below in **Figure F**.

We use a proprietary detection method to reduce the large amount of DC light which is inherent in our optical design. Scale variations or contaminants will cause DC levels to wander and degrade measurement accuracy. Our detection reduces ordinary scale variations to a level of only 1.5 nanometer! This is well below our standard, minimum resolution of 0.01 micron.

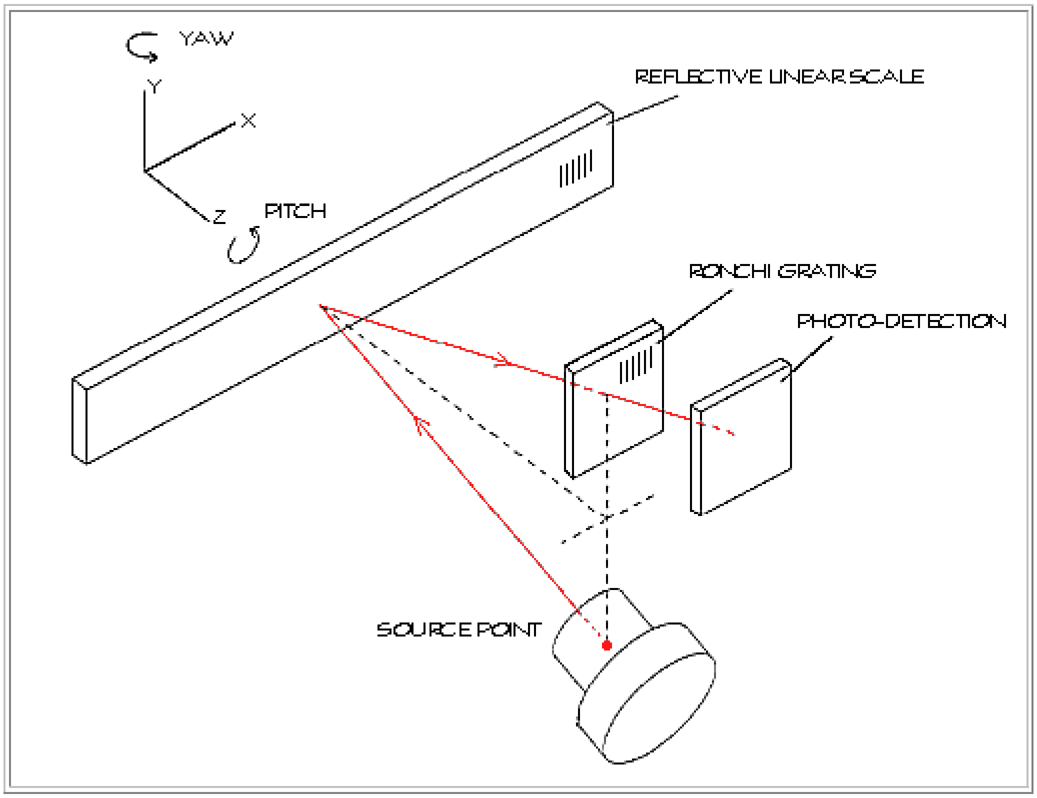

Figure F. Layout for the basic unit

We then have a position sensor which is impervious to wavelength variations, atmospheric effects, off-axis translations, strongly resistant to contamination, and has wide alignment tolerances. In addition, this is accomplished using very few components.

By using the unique properties on our special plane, we end up with a measurement device which is accurate, stable, reliable.

The imaged laser spot is located directly on the Ronchi grating which insures that our required geometry is realized. In the region of the laser spot there are no grating lines. As before, light which is positively and negatively diffracted from the scale, interferes to form fringes on the target plane (Ronchi grating) which have exactly the same line spacing as the scale. There are of course other fringes and DC light which complicate useful photo detection.

We see that the light returning from the scale is again brought to a focus on the "Image Plane". There we have an image of the original focused laser spot. Diffraction from the scale, though, generates pseudo-spots which are displaced to and fro in **x** on the image plane. The Ronchi grating has the effect of mixing these two spots, one with the other, providing interference. The spatial filter located on the image plane passes only these two spots. The beams are allowed to re-expand, but now all DC light is rejected. Fringe contrast here is very high, and unlike the standard unit. The unwanted effects of scale contaminants and the inherent surplus DC light are eliminated.

The point source diffraction principles discussed for the our basic Linear Encoder can be expanded upon to provide a more precise unit. Simply using finer scales and employing the standard geometry is a possibility. However, doing so results in decreased alignment tolerances. In order to improve these tolerances it is necessary to reduce the size of the beam at the scale. We can do this by moving the source point closer to the scale. This is achieved by using the image of a laser diode instead of the diode itself. This image can be placed arbitrarily close to the scale.

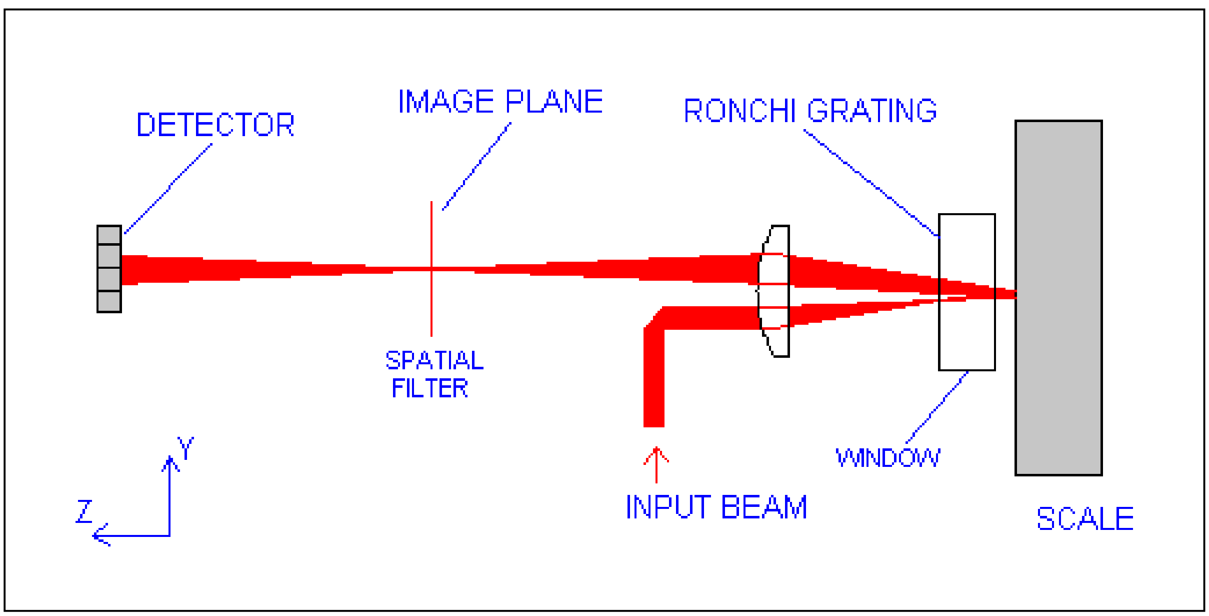

Photo Detection:

Photo detection is accomplished using a 4-element linear array detector. The "pitch" angle of the internal hologram is adjusted so that one fringe spans the array. Of the elements A, B, C, D; A and C are subtracted to form one quadrature signal, and B and D are subtracted to form the other. This provides even more DC rejection.

Alignment Tolerances:

This geometry is particularly insensitive to yaw. Yaw effects are related to beam size at the scale, which have been reduced, but in the plane of diffraction our incidence angle is zero, and the signal response becomes an even function of yaw, centered on zero.

As for pitch, the beam size is made smaller by locating the source point close to the scale, and by orienting the laser diode with its smallest divergence in the vertical direction, **y**. This orientation happens to also maximize our diffraction overlap (and signal) in the **x** direction.

Our new Linear Encoders typically incorporates a 2 micron scale, and therefore a 1 micron signal period. The sine and cosine analog outputs very strongly reject scale contaminants. As with the older encoders, the path length differences between the interfering beams is zero so that wavelength and atmospheric effects are eliminated. Also, the newer encoders have the same **z** axis indifference. Pitch and yaw alignment tolerances are very high, especially given the resolution.

The newer device incorporates the same electronics as the older one, so we have selectable resolutions. The finest quadrature resolution is 2.5 nanometer where the stability is even lower. High speed outputs are also available.