Key Notes to the Advancement of Optical Scanning

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Retired*

Abstract

In forming an historical perspective of the development of optical scanning, we ask a probing question: *What was the first major **optical scanning** innovation?* We offer one having unexpected attributes, and seek audience ideas. We then demonstrate the pioneering work in Optical Scanning for information transfer -- some created long before we arrived on the scene. Our job has been and is -- *Make it **Faster** and **Better**.*

The body of the presentation addresses how our technology advanced to this useful state. We then view some key signs of this progress Major device development starts with the *mirrored reflectors,* articulated in *oscillation* or in *rotation.* The *High Inertia* catagory concldues with *holographic* scanning. The *Low Inertia* groups, initiated with the *Oscillatory* scanners, continue into the *Acoustooptic* and the very fast *Electrooptic* domains. The quest for economic practicality gains special attention for the *control of scanned beam misplacement,* leading to precise opto–mechanical pixel and line positioning from cost–effective articulating scanning devices. The development concludes by describing some recent advancing technogies which utilize novel disciplines for precise low inertia random–access scanning.

Some of the early progress was derived from work conducted by research groups which limited information distribution. Such constraint resulted from, e.g, security requirements, or specialized operational fields of interest, or simply from lack of interaction. Consequently, with limited early information transfer, other groups having related expertise or interest were delayed in the pursuit of this development. Commendation is accorded to the *SPIE* for recognizing early in the '70s (our First Conference entitled, *Laser Recording,* Vol. 53) the need for effective information transfer, by supporting and sustaining ***the*** forums for this technology for more than three decades.

Key Words

1. **Optical Scanning**
2. **History of Optical Scanning**
3. **Scanner Device Evolution**
4. **High Inertia Scanners**
5. **Low Inertia Scanners**

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I Introduction

What is **Optical Scanning?**
-- A Systematic articulation of light, for information transfer.

Then, what qualifies as **the first major optical scanning innovation?**
-- My vote is for **smoke signals!** And, a definition: *Heated aerosol groups, rising and scattering light sequentially to convey information, as viewed from a distance.* Notably, a *digital, binary serial* system!

Then, What qualifies for modern optical scanning?
-- We require vastly more information transfer in much less time ***with much more convenient apparatus!***

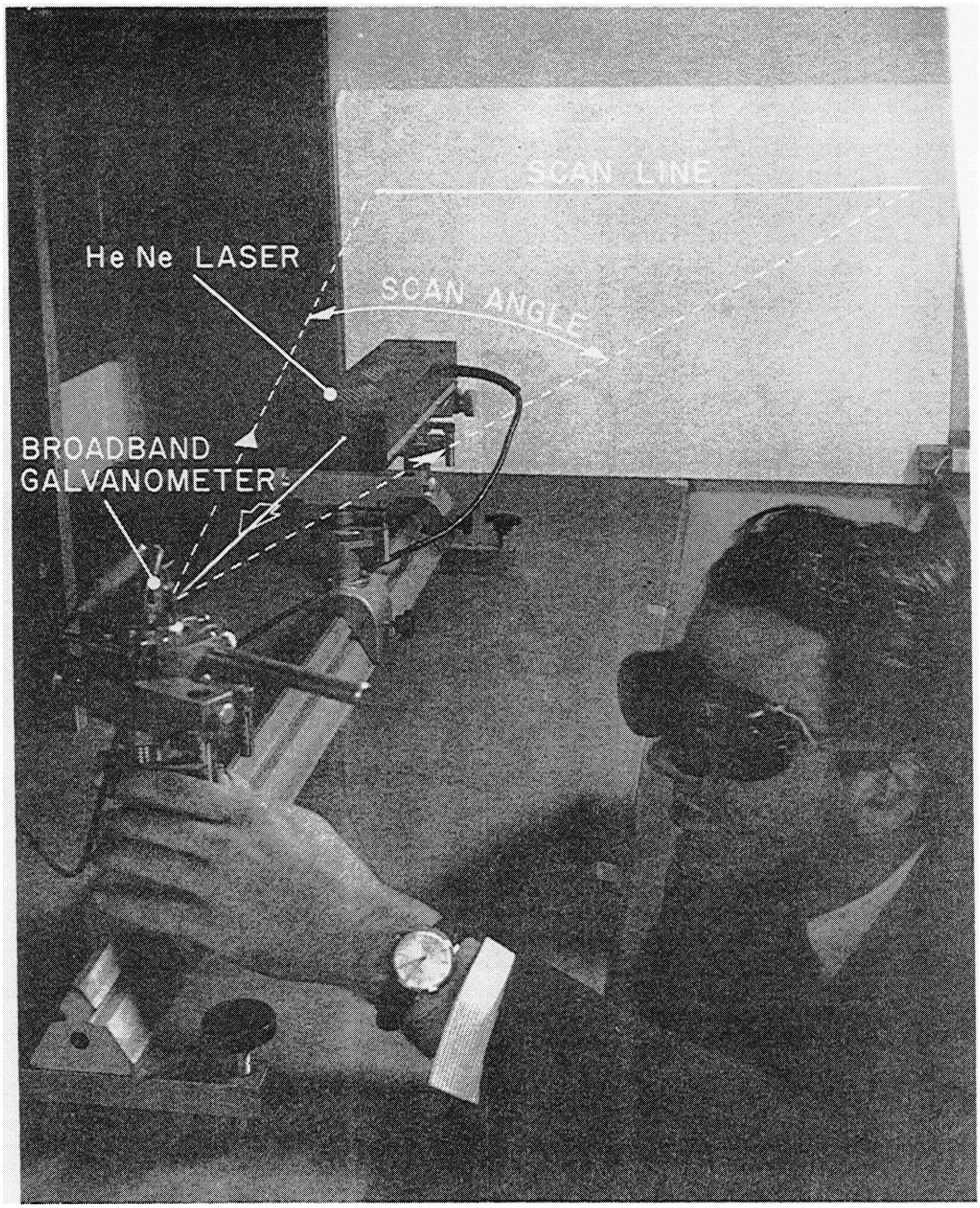
II The Adventure of Advances

It was long clear that controlled light traveled fast and far, and was well confined over distance. Note, the *heliograph;* the sunlit mirror "blinker" used ship-to-shore, etc. In the confined space of instruments for data/image transfer, starting in the 1930s, the historic oscillographs used a pen-shaped mirrored moving-coil galvanometer[1] mounted in a strong permanent magnetic field. Its mm-width mirror on a taut-wire suspension scanned light spots derived from an incoherent source. Fig. 1 is a photograph of a simple test in my lab at CBS Labs using a then-available (1964) similar galvanometer, illuminated by laser. The scanned line, barely visible in the photo, was rapid and almost straight. Indeed, this scan viewed in these Labs, renowned for their rotating phosphor anode line-scan CRTs, illustrated in Fig. 2, and super-high resolution electron-beam image recorders, motivated dedicated research in laser scanning technology. Another classic instrument for data/image transfer was the early facsimile[2], employing typically, a variant to the Edison cylinder recorder; i.e., a rotating drum medium transport, with an incoherent light source focussed on the medium. The focussed light was arranged to translate uniformly longitudinally across the rotating drum; continuous light for image scanning, or modulated for recording.

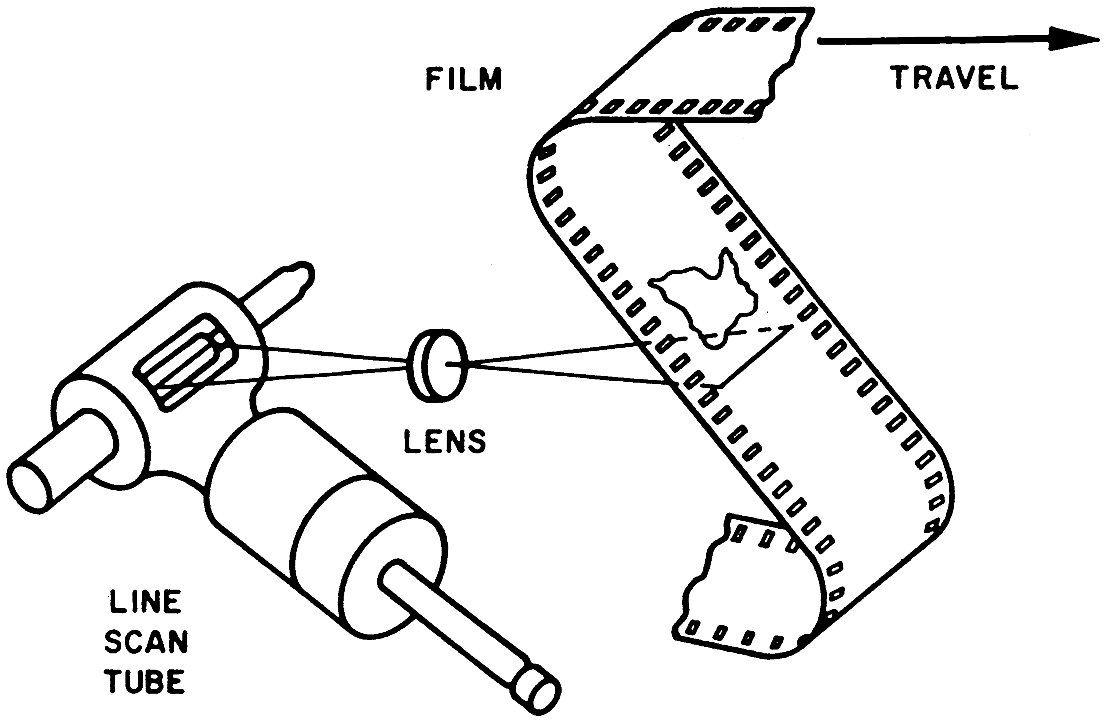
Although the use of light for information transfer was a "given" long before we arrived on the scene, our job was, and still is, to make it *faster* and *better* cost-effectively. "Faster" is synonymous with bit-rate, pixel-rate"; *bandwidth;* even when multiplexed, "Better" is much more complex. In general, *more data per unit space;* but with so little artifact that the information value is optimized. This criterion has many contributing factors. We discuss some of the more critical quality determinants later. For noteworthy recent references to our technology, a new publication[3] provides a comprehensive resource for contemporary laser scanning and its optics, and another[4] offers unifying concepts to the basics and practice of our current and advancing work.

III Progress, in Historical Perspective

Advances in optical scanning now merit special attention. We start with the elegant mirror scanner and optics designed for precise mapping of incoherent infrared radiation. To those in the infrared imaging field, it is the well-known Kennedy Optical System, Fig. 3, patented in 1965[5,6]. Although by no means the



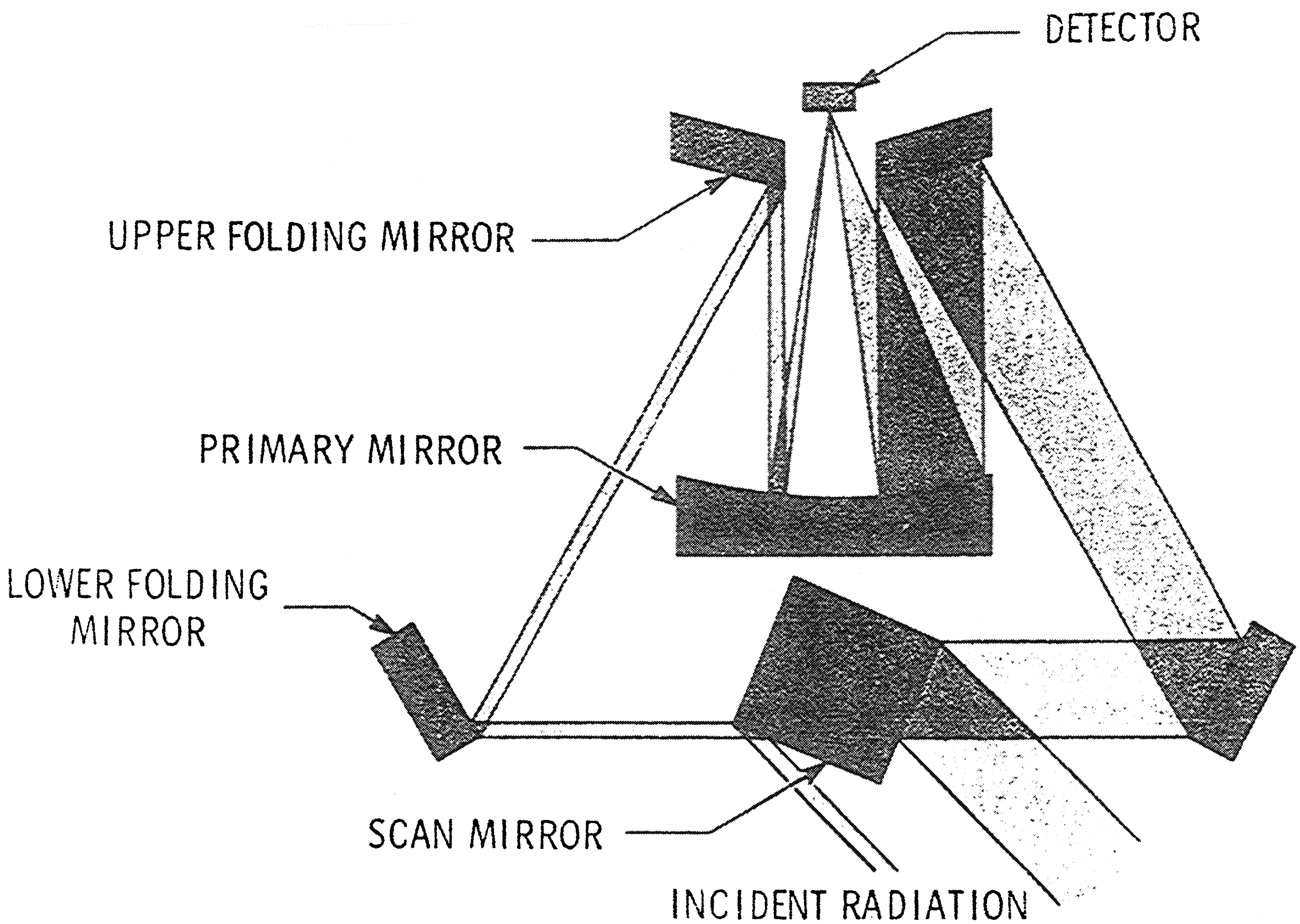
1 Photograph of early broadband galvanometer laser scanning experiment. Input and output beams near–coplanar, to approach straight scan line. (1964).



2 Illustration of CBS Labs' line scan tube (rotating phosphor anode CRT; highest pre–laser technology) in photorecording application (1963).

beginning of intensive work in this field[7,8], it demonstrates the clever use of a (4–sided) rotating polygon and reflective optics. Almost its full aperture is used, while the remotely incoming incident radiation is split and shared progressively on two facets during rotation and then recombined optically on a single detector, providing an almost 90% duty cycle. This *Remote Sensing* operation is identified[4] as *Passive Scanning,* in which the light path is reversed from that for *Active Scanning,* as illuminated by a light source for writing or display. Thus, replacement of the (passive) sensing detector with an appropriate (active) source (e.g., laser), yields a scanned typically collimated output beam. (This scanner is unique in forming a split collimated beam.)

A recent broad representation of novel remote sensing scanners[6] reveals the similarities between the passive and active devices, underscoring the quest by two independent communities for related technologies, separated by security limitations and operational objectives. These same separation factors were also operative in the pioneering development of extremely high performance laser scanner systems created for reconnaissance application starting in 1965, extending into the dynamic commercial development of the graphic arts and laser printing technologies. Subsequent work in the these fields, such as anamorphic error correction and Bragg–angled holographic disc scanners –– which ultimately were replicated effectively, added significantly to the global resources in optical scanning. Our objective is to identify and exemplify this progress.

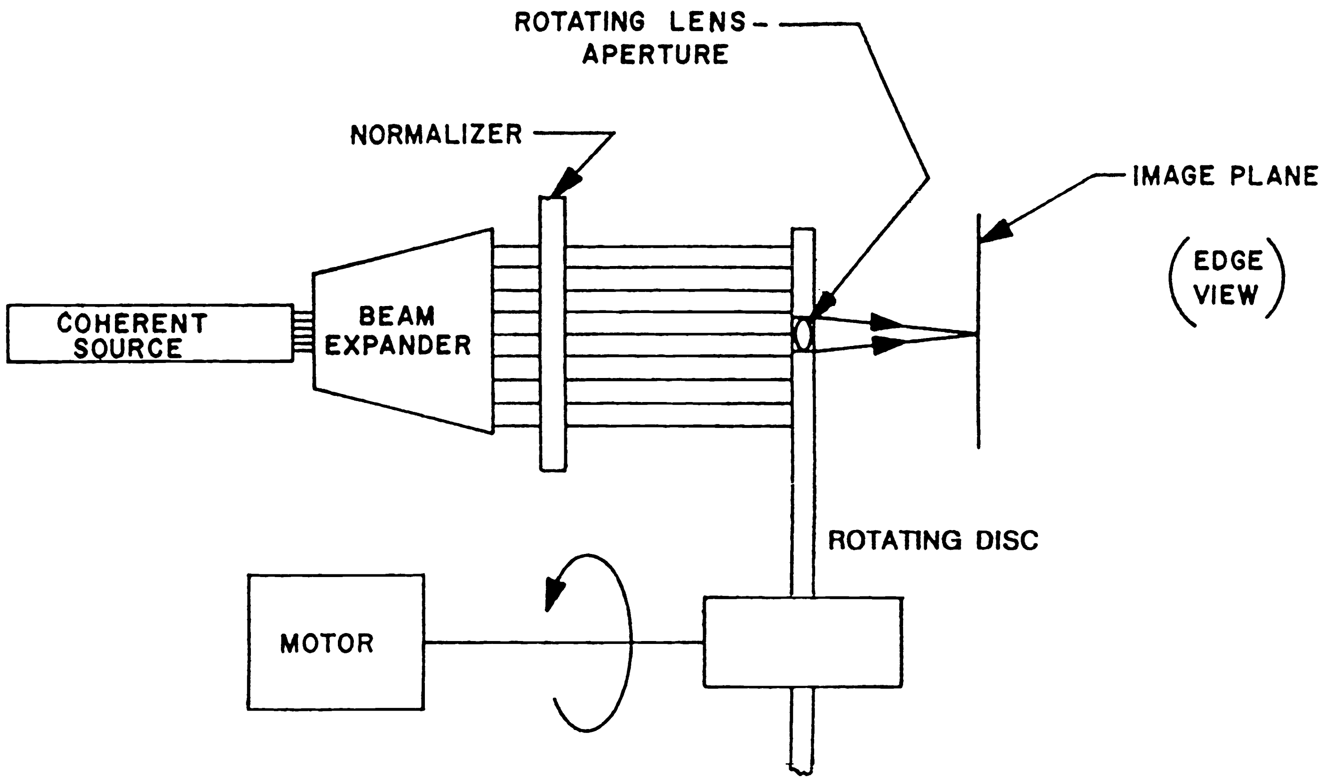


3 Basic Kennedy split–Image optical system, applied to the field of remote sensing, per U.S. Pat. #3,211,046 (1965).

IV Enter, Intensive Work in Laser Scanning

Availability of the HeNe laser in the early 60s inspired much research. In mid–1964, the U.S. Air Force, seeking major advancement in imaging speed and resolution, issued a request for an *"Optical Spot Size Study for Data Extraction From a Transparency".* It required a "coherent source" to form a 2.5μm spot (to $1/e^2$) scanned across a 2–inch field at 500 sweeps/sec., and reading a 200 lp/mm test target. Fig. 4 illustrates the system provided by CBS Labs. It resolved a U.S. Air Force Resolution Target to its 256 lp/mm limit (>6,500 dpi). In this fundamental arrangement, a rotating disc supported five microscope objective lenses spaced equally about its periphery. During rotation, each pair was over–illuminated progressively through expanding optics, for 100% duty cycle. Fig. 4 also renders the first published use of the phrase, *beam expander*, one of several recognized terms* developed from this and related work. Interesting consequences of this work, and the dissemination of these phrases are noted in Appendix 1 of a 1988 publication[9], providing an historical review of holographic scanning, including the relationship of this scanning lens work to that technology.

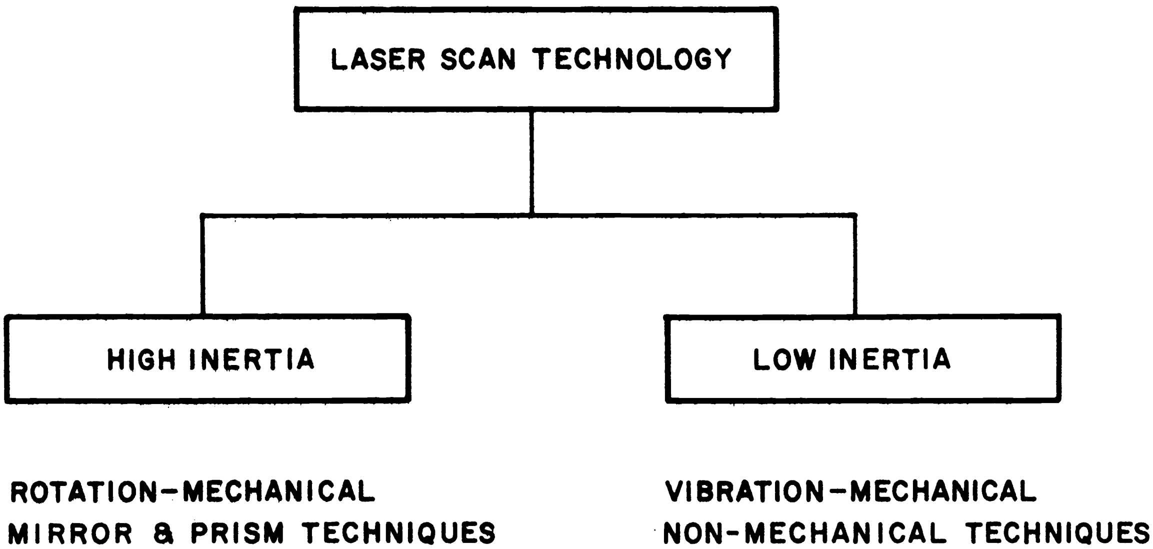
*Notably, *Preobjective, Postobjective* and *Objective* Scanning;
Over– and *Under–illumination.*



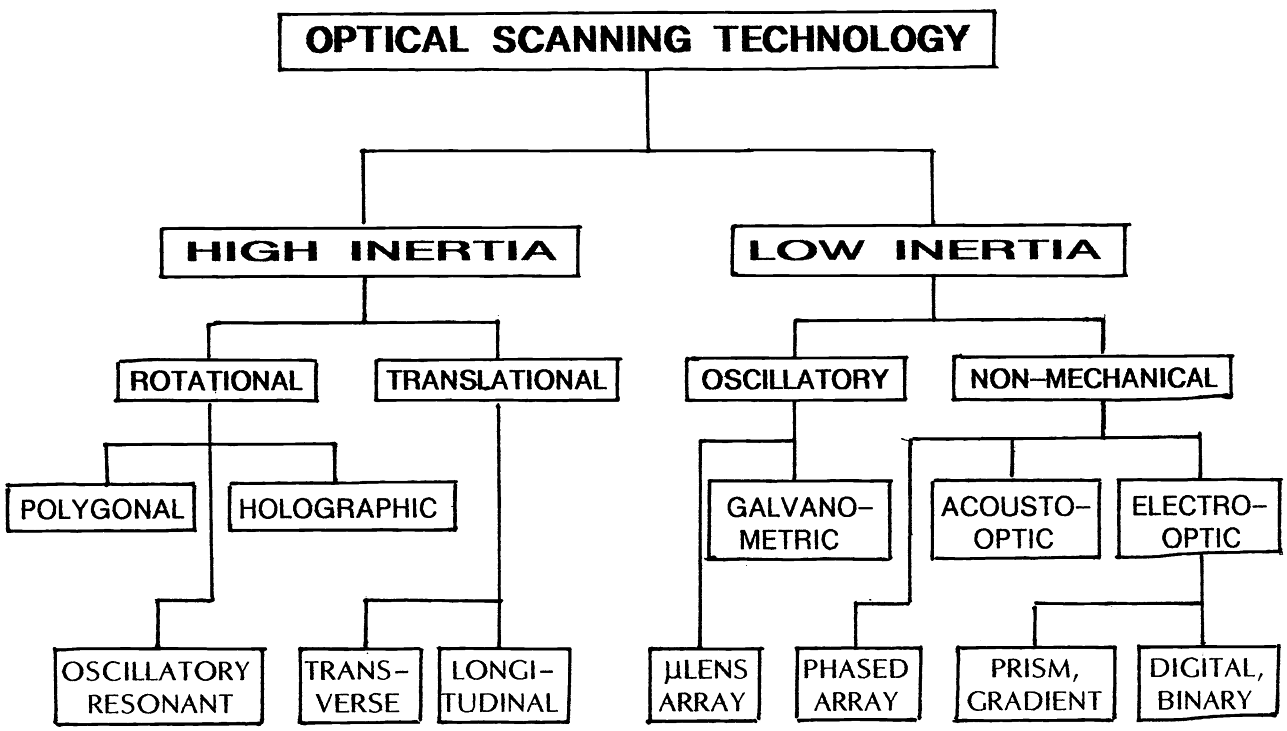
4 Schematic of the first hlgh speed and high resolution laser scanner, providing 500 scans/sec. of a 2.5μm spot over a 51mm format, at 100% duty cycle. Shows first use of the phrase, "beam expander" (1964).

Furthering the evolution of optical scanning technology merits a presentation of its principal options. Fig. 5 is the first such representation[10], published in 1969. Following several published iterations, the most recent[4] appeared in 2002; here as Fig. 6, providing much additional detail, including many of the disciplines to be discussed.

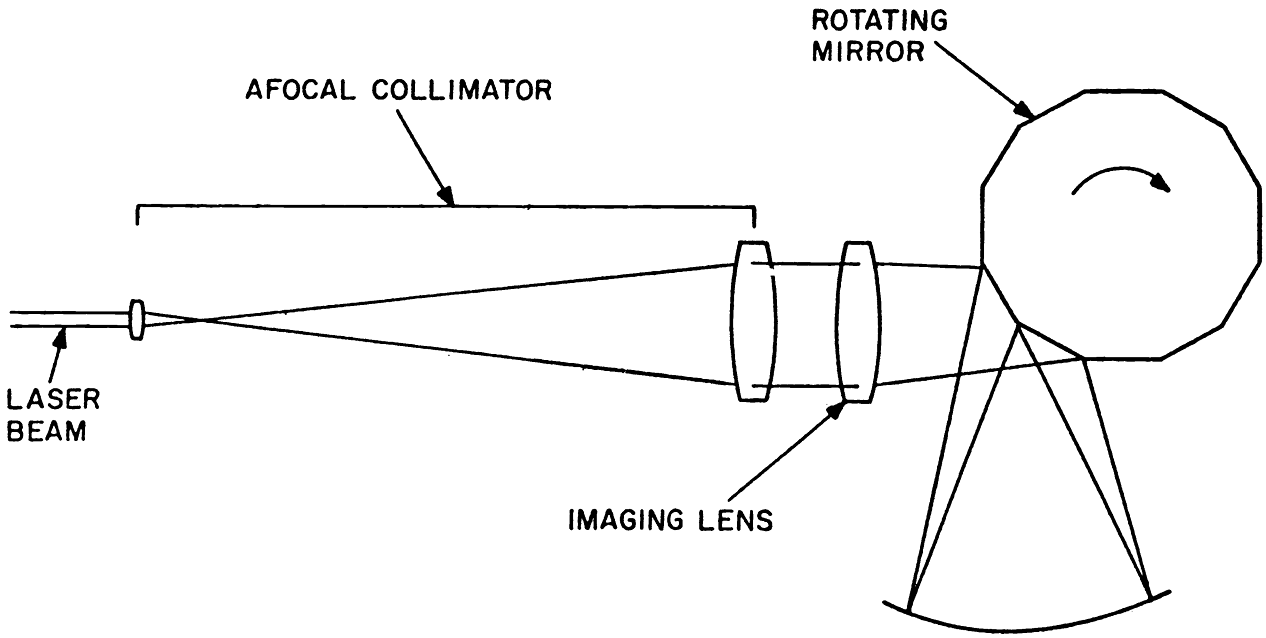
The intense early development of (high inertia) rotational polygons is exemplified in Fig. 7, rendered for the "wideband recording" community[11]. This reference appears in the first of a series of Wideband Recording symposia, formed in 1967 by the Air Force's Rome Air Development Center, and participated by invited research organizations and speakers. This first conference was classified Secret; subsequently declassified. Fig. 7 illustrates the pairs of polygon facets which were overilluminated to maximize aperture size (resolution) and duty cycle. The phrase, "afocal collimator" appears, used by this research group before it recognized the phrase, "beam expander". The (postobjective) arced scan line was preferred to maintain unaberrated spot quality over a wide field, compared to the critical design and production of complex (preobjective) flat field lenses required for extremely high resolution wide field imaging. The arced scan line approached the contour of "cupped film", illustrated 4 years later in a 1971 presentation of the developed system[12], Fig. 8. Film cupping is maintained there rigorously by the "Focal Guides". (Some guides were a single block, machined with a long slot to pass the beam.) The scanner is shown at the instant of ending one line and starting the next.



5 Early organizaton chart of Laser Scan Technology (1969).



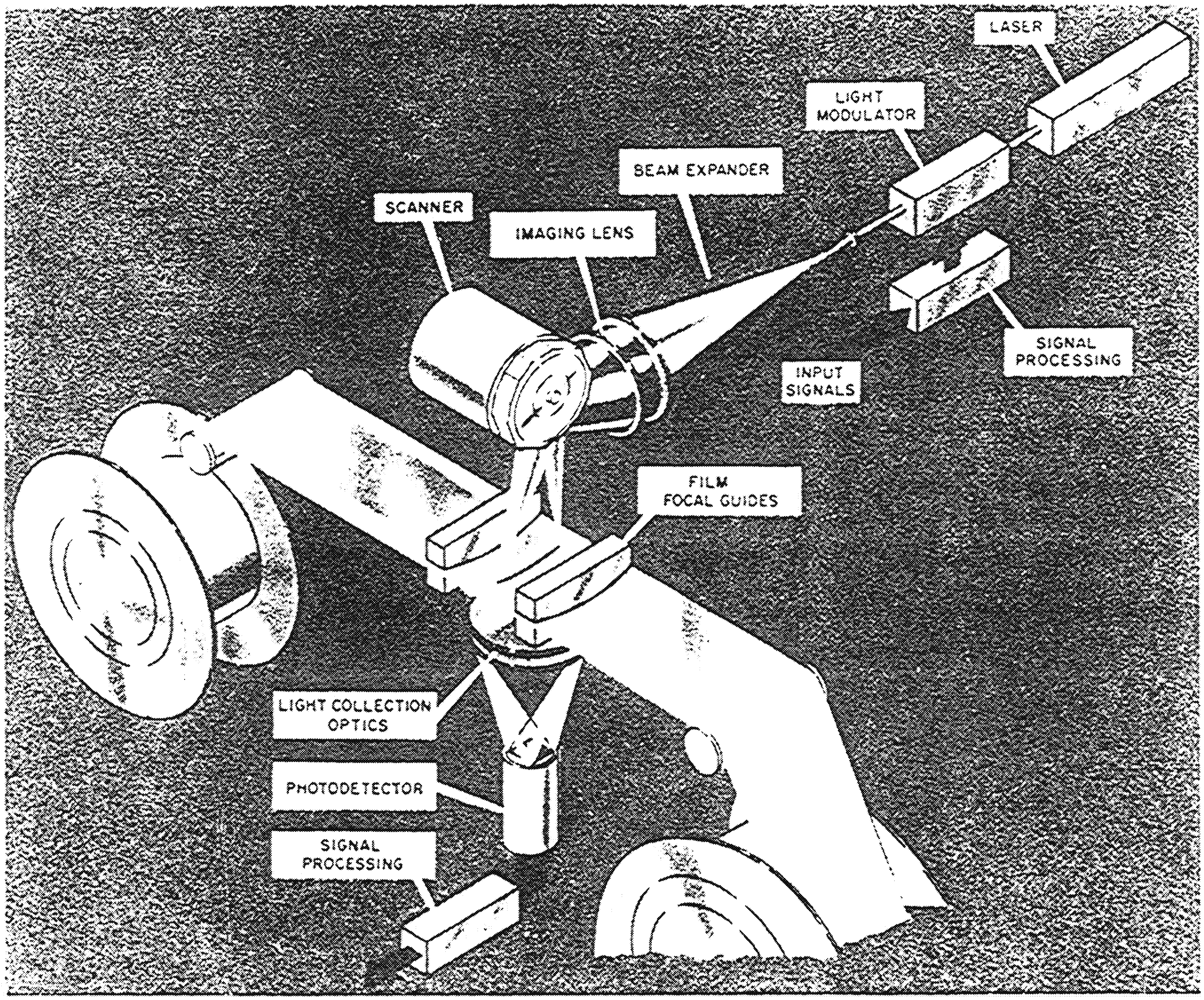
6 Most recent classification of Optical Scanning Technology (2002).



7 Illustration of prismatic polygon laser scanner, overilluminated for 100% duty cycle, providing postobjective arced scan locus (1967, Ref. 11). "Afocal collimator" notation was used by this researach group before they recognized the phrase, "beam expander". See Fig. 8.

A subtle limitation to a perfect match of the scanned focal locus to the film surface is that the arc developed from the above arrangement is non–circular. It follows the form of the Pascal limaçon, for which equations of the scanned locus and spot velocity are developed[13]. Even if the focal guide is shaped to conform to this aspheric surface, the spot velocity remains not perfectly uniform. Achievement of both a circular arc and uniform spot velocity is provided only by a scanner operating in *radial symmetry* [4,9,13,14]. This is accomplished for this "wideband recording" task with a rotating pyramidal polygon operating "tilted axis", as illustrated in Fig. 9; a 1966 design for which the *circular locus theorem*[14] was originally developed. A perspective rendering of this cupped film scanner appears in Fig. 10. This configuration formed the key ingredient of a celebrated photoreconnaissance system; much used, including over Southeast Asia. Its classified name was declassified by President Johnson when he presented its timely detailed images at a televised press conference and answered a question seeking the source of the images –– revealing its name, *Compass Link*.

The simplest form of radially symmetric system is that of Fig. 11 from a 1971 publication[15]. This basic "internal drum" type scanner was used effectively later in graphic arts recorders. Here, the scanner/optics assembly is in a fixed position while the medium is transported. The converse arrangement is a popular alternate. The rotating single facet (≃45° to the rotating axis) is aligned coaxially with the optical axis to maintain the scan locus on the circular storage medium. (The beam appears illustrated awkwardly here; converging on the facet rather than filling the facet to focus after reflection on the "film plane".) This type of system could have been employed on the above extremely high performance tasks, except for its very lossy duty cycle for practical 5–inch film cupping, imposing correspondingly–increased (already) high shaft speed and bandwidth.

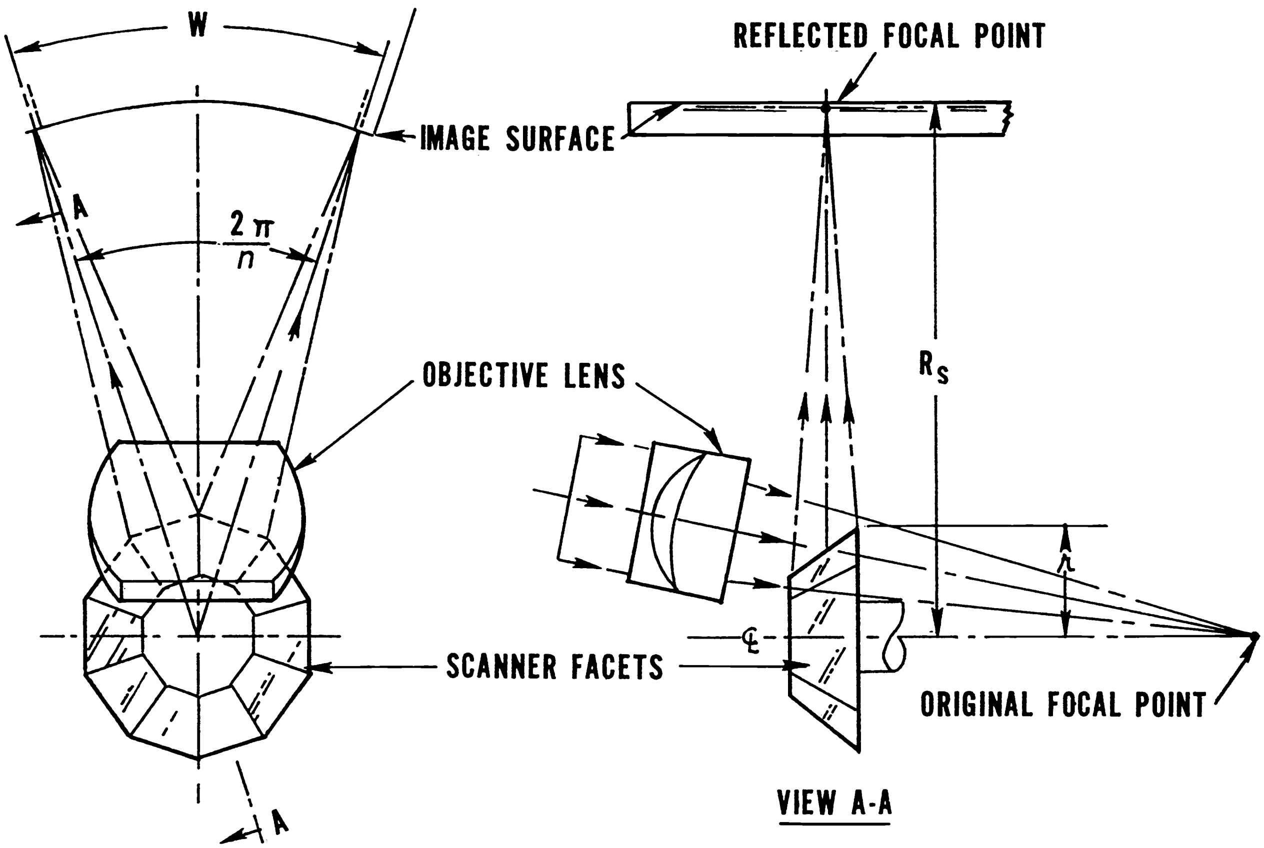


8 Pictorial of the Fig. 7 system, showing film "cupping" to match the arced scan locus. This typifies a high-performance scanner-recorder, to serve the "wideband recording" community (1971).

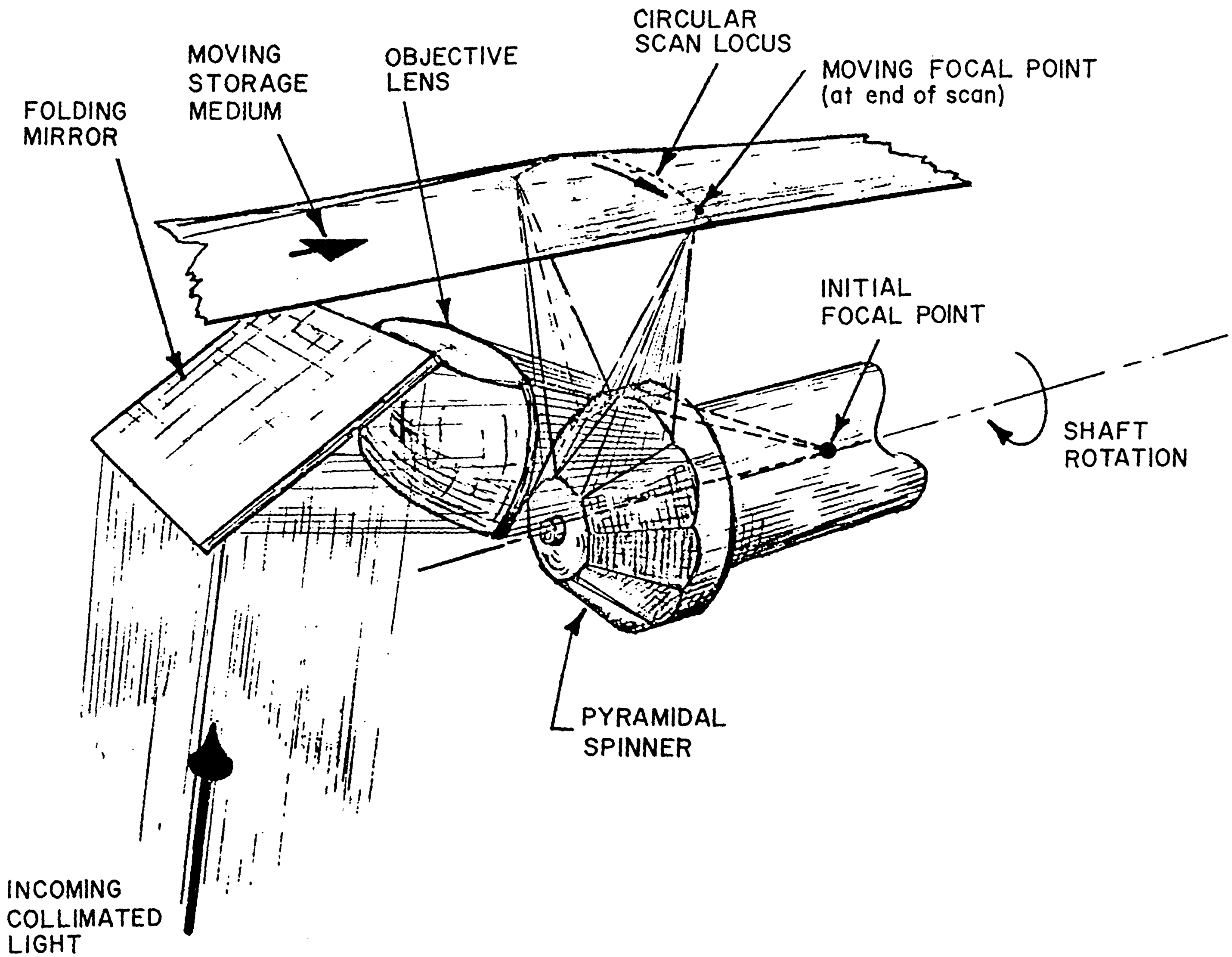
Having entered fairly familiar operational territory, we interrupt coverage of this important field of polygonal scanners, to return later with some special attention to its scan uniformity. Following an earlier clue regarding the relationship of Fig. 4 to *holographic scanning,* which appears in the same Fig. 6 family of **high inertia rotational scanners**, that development will now be addressed.

V Holographic Scanning

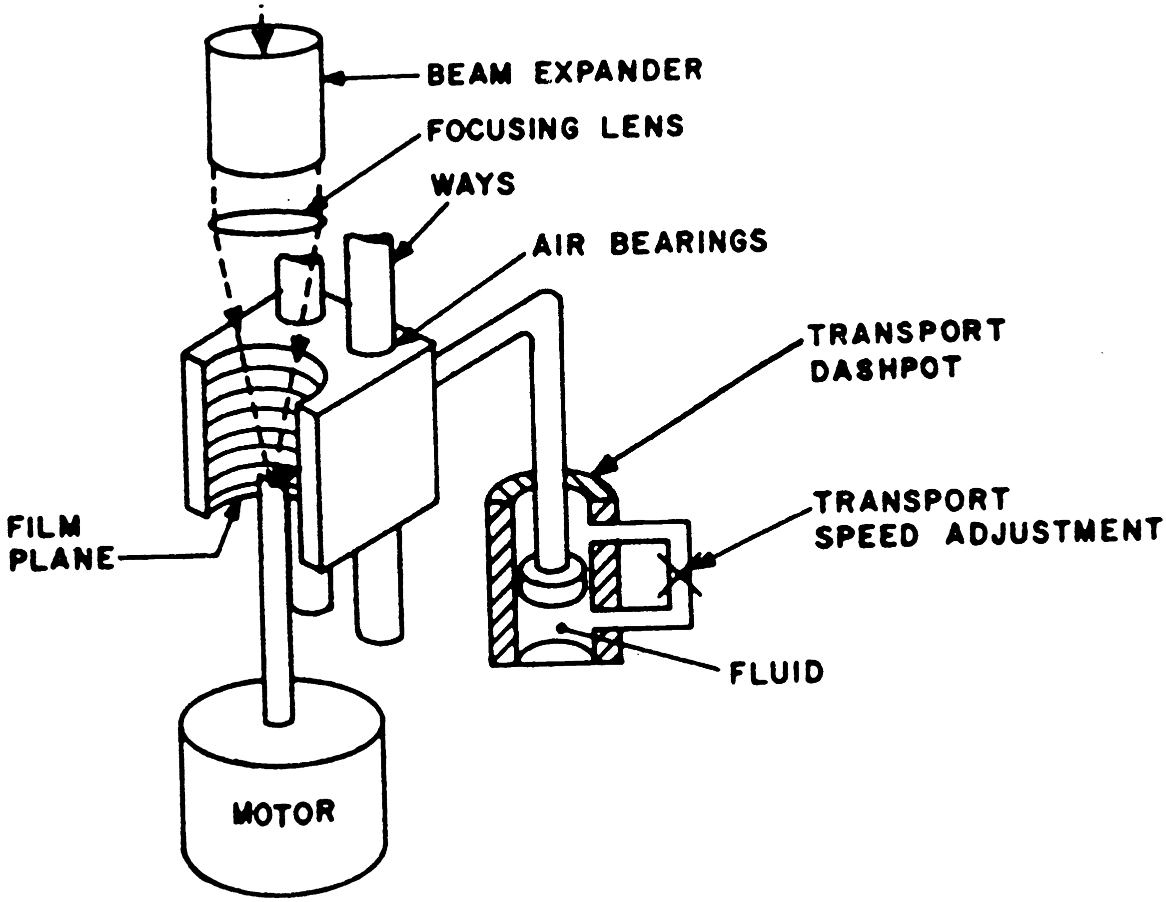
Quite surprisingly, a significant work which bears directly on holographic scanning was patented[16] **in 1934** by the noted pioneer in television scanning, Hollis Baird. The first page of that patent is reproduced and discussed in Appendix 1 of the earlier-cited publication[9] on holographic scanning. It shows a



9 Design of the *Tilted–Axis* postobjective pyramidal scanner. Original focal point intersects rotating axis, to provide scanned radial symmetry for precise cirlcular scan locus; and smaller objective lens operates on–axis to illuminate a pyramidal polygon (1965).



10 Rendering of *Tilted–Axis* configuration of Fig. 9. Applied in major wideband scanning–recording operations. U.S. Pat #3,619,039 (1971).



11 Single facet (monogon) in early "internal drum" configuration. With input beam co-axial with rotating axis, radial symmetry more apparent than in Figs. 9 & 10 (1971).

narrow cylindrical drum embedded with a linear array of *zone plate lenses*. They are illuminated from within the cylinder by a fixed incoherent light source to project (upon rotation) a series of scanned focused arcs outside the cylinder. Further, Baird anticipated the zone plates to be embossed on a thin flexible band which forms the cylinder. Also, photographic reduction of the zone plates from a larger master for uniformity; and further, changing the reduction ratios to vary the focal lengths. So dominant is this **1931–filed** invention that it frustrated issuance of at least one more–recent holographic scanning patent, and some claims in others. The rejected patent mounted small holograms in both a cylinder and disc, similar to the earlier **1928** patent by Jenkins[17], who added lenses in a rotating disc. That disc was similar to the classic **1884** spiral of holes in a disc, created by the most recognized early television pioneer, Nipkow.

Dennis Gabor, the inventor of holography, was a classmate in Hungary of Peter Goldmark, President of CBS Labs. Gabor served as Staff Scientist, while this author was Staff Physicist to CBS Labs, fostering a unique and memorable exposure to this brilliant innovator. This period was before, during and after his 1971 Nobel Prize honoring his creative work and his three 1948–51 publications[18], in which he even coined the name, "hologram".

Appendix 1 in the earlier-cited publication[9] presents a comprehensive historical review of hololgraphic scanning, including discussions of --

- D. Gabor's "New Method of Optical Scanning", April 1965; an acousto-optic traveling zone lens. This technique did not appear in the literature until a paper by Foster, et al[19] was presented in 1970. It is discussed in Section VII.

- D. Gabor's "Holographic Scanning Disc", April 1967. The scanned convergent beam remains paraxial to the rotating axis, as in Fig. 4.

- I. Cindrich's *Applied Optics* paper[20], Sept. 1967, describing scanning holographic discs with very perceptive presentations of theory and practice.

- L. Beiser's *HoloFacet* scanner, May 1969. This first patented holographic scanner[21], illuminated per Figs. 9 & 10, provided 20,000 pixels/scan at 200 Mpix/s. It received the IR-100 Award of 1973. The prototype, with reflective holograms processed on a 4" Dia. beryllium sphere, now resides in the permanent collection of the Smithsonian Institution.

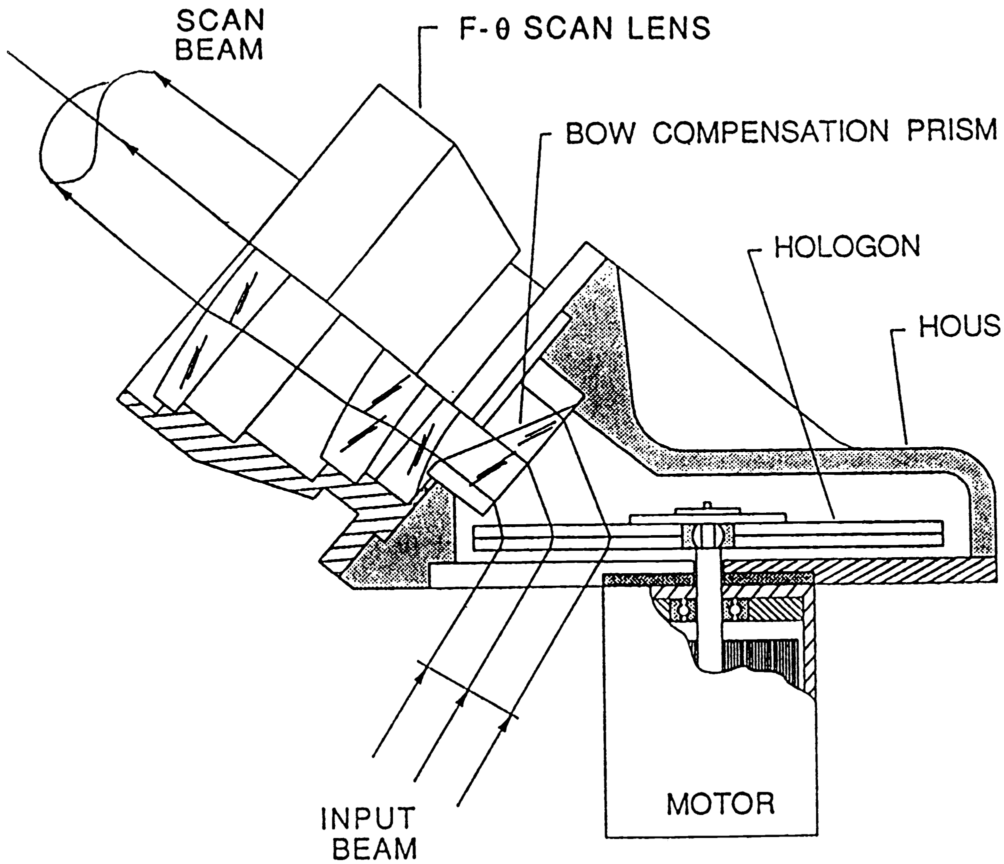
It was not until 1975 that work was published by organizations such as IBM and Xerox, which targeted the more moderate but still demanding application to business graphics:

- R. Pole's, Apr. 1975 (of IBM) cylindrical scanner[22,23]; basically similar to Baird's zone-lens cylinder, (See Sec. V.), except that it was illuminated radially symmetric, and it provided for light retrocollection to access the return signal for data reading. The patent allowance was primarily for this provision.

- O. Bryngdahl's, Oct. 1975 (of Xerox) computer-generated diffractive elements on translating or rotating substrates[24], for greater control over the scanning "holograms" in one, two or three dimensions. This was followed in 1976 by a more comprehensive presentation with co-author Wai-Hon Lee[25].

- C. Kramer's (of Xerox and Holotek Ltd.) series of innovations, 1976-1981[26,27,28], which matured to a prominent technique; adaptable to the more demanding commercial applications of the graphic arts: plane linear holographic gratings disposed around a transmissive disc; operating at the Bragg angle, and positioned preobjective.

Fig. 12 illustrates this "hologon" configuration. A feature of this system is that it renders a significant reduction to cross-scan line misplacement due to shaft wobble, satisfying one of Kramer's earliest design objectives automatically, without recourse to earlier novel[26,27] mechanical intervention. The originally-derived Bragg angle of 45° was reduced to 30°, to raise the diffraction efficiency and to reduce polarization sensitivity to disc (grating) rotation[4]. A trade-off motivated adding the prism to compensate for the resulting introduced line bow. Appendices 2 and 3 of the prior reference[9] provide unique documentations of this development[28] and of a related one translated from the Russian[29]. The analytic derivations which draw similar conclusions differ substantially. Per Appendix 1 discussion[9], priority of invention is credited to Kramer with early filing of his work. Most contemporary holographic disk scanners use adaptations of these principles.



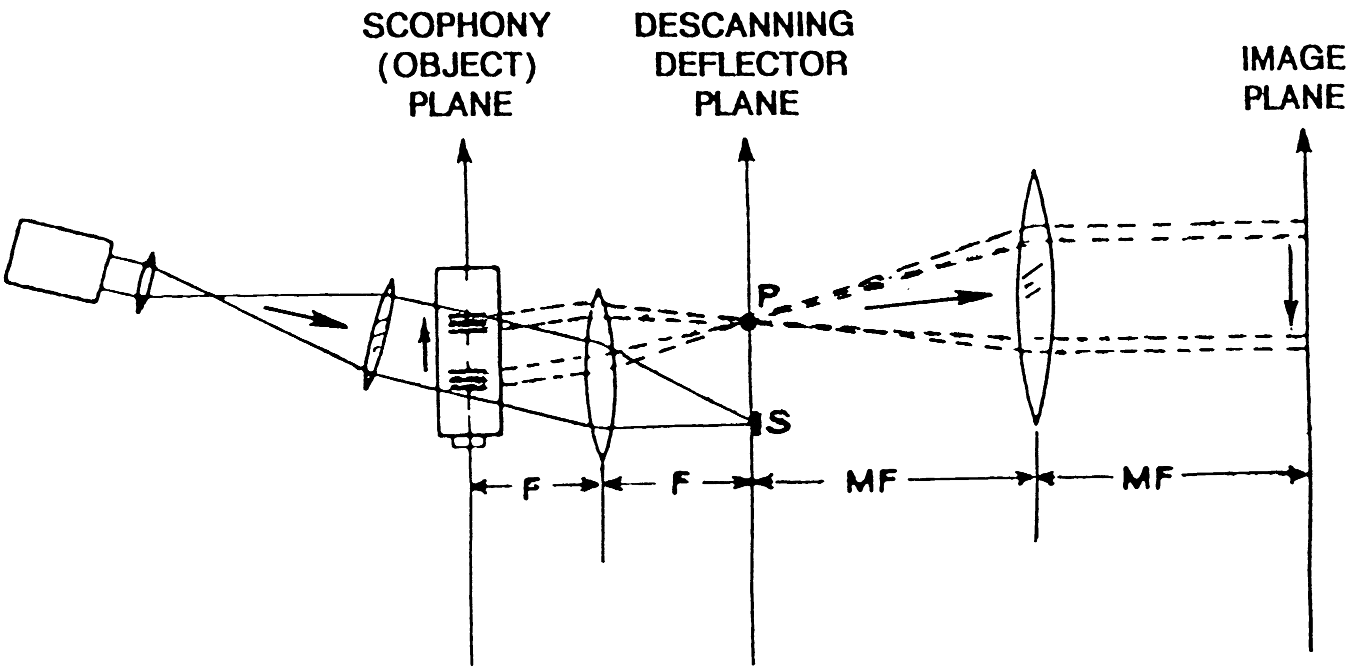
12 Current form of plane linear grating (Hologon) holographic disc scanner by Kramer (1981). See text and references 28 & 9, Appendix 3.

VI Oscillatory Scanners

These components, identified earlier as among the first developed and tested (Fig. 1), have matured as prominent light beam deflectors, providing highly controlled accuracy and repeatability. They fall into three catagories, reviewed and compared recently[4]: *Broadband Galvanometers, Resonant Scanners,* and the newer *Fast Steering Mirrors.* The characteristics and performance of the first two "classic" types have been covered extensively in the literature[6,7,13], with a comprehensive review by Montagu[30] published recently. The third type (fast steering mirror, e.g., by Ball Aerospace or Physik Instrumente, and others) comprises a plane mirror in a flexure suspension, actuated at opposing sides by X&Y push–pull drivers; e.g., voice–coil by Ball, or piezo–driven by P.I. It provides rapid 2–axis scan from a single mirror, albeit at narrower scan angles from a (typiclly) larger mirror. (Note that with a large illumination–filled aperture, the resolution, in elements per scan, could be very high.)

The extensive review noted above[30] includes a summary of the historical development of the galvo–type scanner, capsulized here : --

• These devices are variations of d'Arsonval's 1880 classic galvanometer; a measuring device still employed in many moving–coil–type electrical meters. Adapted rapidly with an added mirror, they formed the pen–shaped scanners



13 Scophony scanner optics. Input illumination fills scophony modulator–deflector. Two bursts (e.g.) of "object" acoustic wave travel "upward", diffracting two beams; focused by 1st lens at point P. They continue through 2nd lens to project two spots on Image Plane, traveling "downward". (Zero order is absorbed by stop S.) A deflector near point P (not shown) scans beams in reverse to immobilize spots on Image Plane. Subsequent scans form stationary raster image of spots. (Refs. 34&35, 1939).

discussed in Section II, serving effectively in sound–track and waveform recording instrumentation.

• The first commercial laser–illuminated galvos in the early 1960s were open–loop devices. In the later 1960s appeared the moving–iron scanners; more compact and efficient than available from the early moving coil types. They were adapted in the early 1970s with position servos as closed–loop scanners, to render increased bandwidth and accuracy.

• In the late 1980s came availability of high energy permanent magnets -- adapted rapidly as moving–magnet galvo torque motors, to exhibit much greater peak torque.

• During the 1990s, advanced computer control and design optimization served to enhance even the best galvanometers, in real–time, with improved periodic and aperiodic armature motion and stability.

The intent of all these devices is to utilize low inertia vibrating armatures and loads. While the galvanometer and the fast–steering mirror operate at low–Q broadband to allow forming, e.g., a linearized sawtooth scan, there is an anomaly in the common classification of the resonant scanner as a low inertia deflector[4].

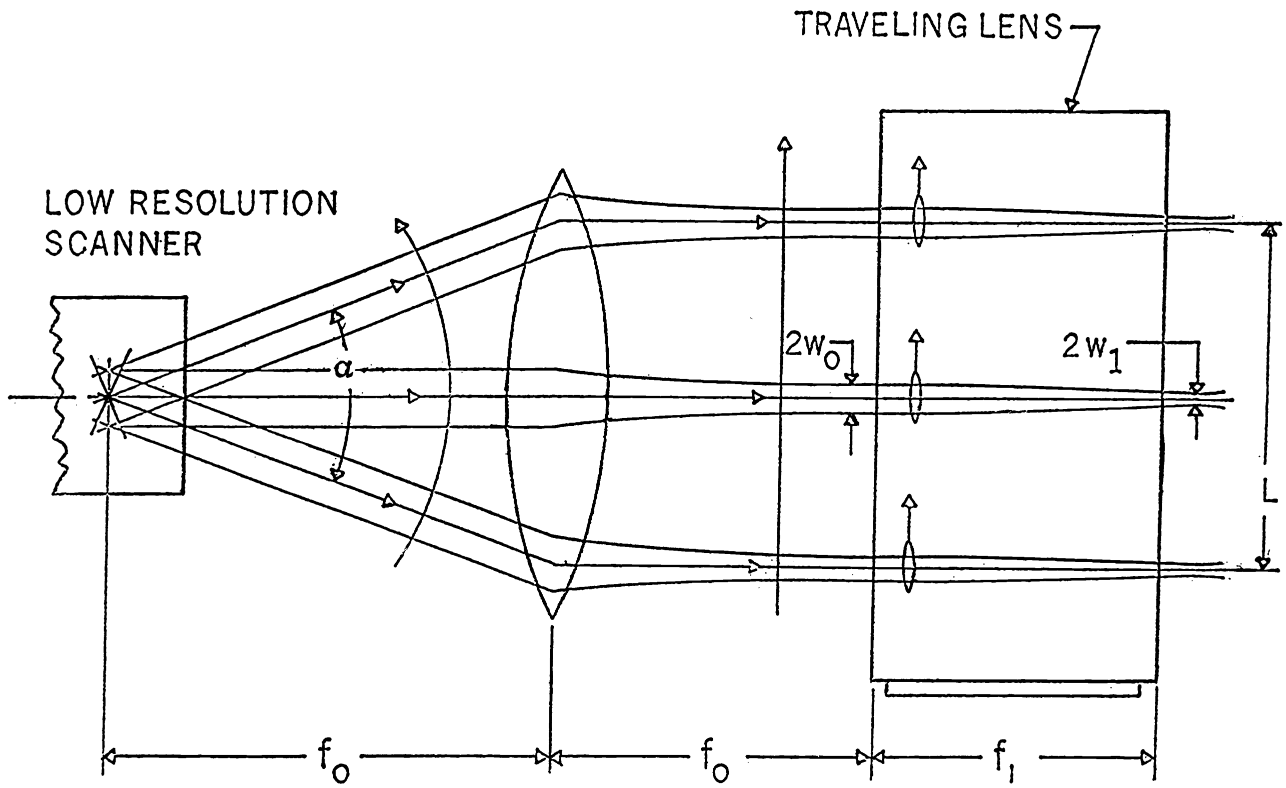
Operating at high–Q and at a high resonant frequency, it forms its fundamental sinusoidal scan, having the invariance typical of a high inertia device (such as a pendulum). To form uniform pixel spacing, the pixel frequency must be varied. Corrective programming of the data stream may be instituted to transform the incoming uniform pixel timing, to simulate a velocity–linearized scan[4,31] over most of its ½–sine "forward" traverse. The resonant scanner is represented uniquely as a high inertia device in the Technology Comparison Chart, Fig. 6.

VII Acoustooptic Scanners

This technology and most to follow sit squarely in the low inertia domain. Acoustooptics is about as old as galvanometrics; researched and described in 1932 by Debye and Sears[32] and by Lucas and Biquard[33]. Its theory and design practice was reviewed with other laser scanning technology as early as 1974[13], and most recently, in 2002[4] and in 2004[3]. These publications also provide substantive reference to earlier detailed technology and materials evaluations. While the familiar acoustooptic scanner type has been well documented, and its operation is well represented, some pioneering and special configurations are noteworthy here.

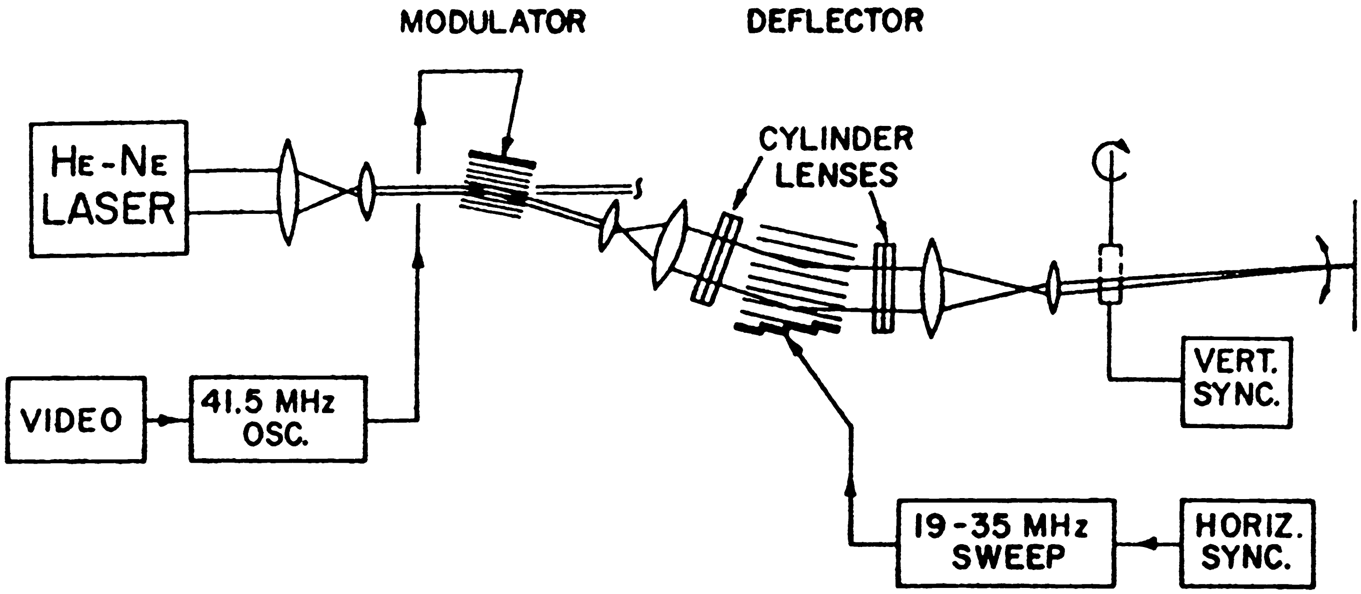
The first systematic work using the acoustooptic effect appeared in 1937; only 5 years after the two publications cited above. Rarely covered in review literature, the Scophony System[34] remains one of the most significant principles, reappearing in video projection optics. Fig. 13 illustrates its basic operation, adapted from a major reference[35] and a review[4]. Illumination, from the left, is expanded broadly before entering the Scophony cell. For simplicity, only two data bursts of acoustic wave are shown traveling "upward" within the broad beam. Two (Bragg) diffracted narrow beams exit the cell, are focused by a first lens to point P (Fourier transform of the data distributed in the cell), while the zero–order focus appears at point S, where it is blocked. The rays leaving P expand into and are collimated by the second lens, arriving at the Image Plane with the two data points scanning "downward" (magnified by M). Adding a "de–scanner" in the vicinity of P, with scanned velocity complementary to that in the Scophony cell, forms a statioary two–point image. For a real image, the Scophony cell both modulates and scans the image line segments. Subsequent scans are formed into a raster, creating the complete stable image. This ingenious system requires additional attention[4], primarily for imaging coherent and partially–coherent light –– unanticipated in 1937!

An early creative adaptation in acoustooptic scanning is the *Traveling Lens.* This was identified in Section V as analyzed by Dennis Gabor in 1965; five years before its independent development by Foster et al[19] of California's Zenith Labs in 1970. Its makes novel use of a traveling acoustic wave in a long transparent cell. The wave compresses and rarifies the interaction material, index–changing into synthetic small lenses traveling along the cell at a high acoustic velocity. An entering "low resolution" scanned laser beam tracks one traveling lens, to be focused into a smaller output spot, forming a "higher resolution" scan over the full format. Fig. 14 illustrates the Foster design. The prior reference[4] expands on this and on related significant R&D at Harris Corp[36]. A frequency "chirp" method was developed at Isomet Corp[37] to form an individual *diffractive* traveling lens.



14 The Foster Traveling Lens. Low Resolution Scanner feeds the Traveling Lens through a passive (telecentric) lens. An acoustic transducer at bottom of Traveling Lens forms synthetic small lens traveling "Upward" synchronously with the spot velocity of the Low Resolution Scanner. Synthesized lens focuses original scanned spot of size $2w_0$ to the smaller size $2w_1$ over format L, multiplying resolution by the ratio w_0/w_1. (Ref. 19, 1970).

Intensive early work toward our more familiar acoustooptic scanning was that conducted by researchers at Zenith Corporation[38] in 1966. The team, led by A. Korpel and R. Adler, V.P. of Research, formulated, designed and assembled the first NTSC TV laser display using an acoustooptic horizontal scanner and a galvo vertical scanner. Recall that NTSC TV horizontal scan requires a sawtooth at 15,750 Hz! (Vertical, at 60Hz.) Further challenging, the interaction material was simply *water,* and the acoustic transducer was a *phased-array* (Ref. Section Xi), providing continuous Bragg-angle match for higher diffraction efficiency during full scan! And, the video modulator was also acoustooptic. A schematic of this remarkable achievement appears as Fig. 15. I was privileged to have seen this milestone in 1966 with Peter Goldmark, President of CBS Labs, and had valued discussions with the research team during a special visit to Chicago's Zenith Labs.



15 The early Zenith Laser TV display system, using phased–array acoustic transducer for the AO horizontal deflector. Note beam compression and expansion before and after the AO Modulator, and reverse process around the AO Deflector. (Ref. 38, 1966).

VIII Electrooptic Scanners

The quadratic electrooptic effect was discovered by J. Kerr back in 1875, and the linear EO effect was researched and reported by F. Pockels[39] in 1906. The original quadratic material, (liquid) nitrobenzene, remains prominent today, and the important linear materials, KDP and KD*P, still used, were investigated and reported by Zwicker and Scherrer[40] in 1943; over 60 years ago. But, as in the above described histories, it was not until the laser became available in the early 1960s, that intensive work was conducted in electrooptic deflection[10,13].

The field of electrooptic scanning may be divided into two generic classes; analog and digital. Intensive R&D was conducted in the '60s in both techniques, while continuing work is primarily in the analog domain. One analog form is recognized as an assembly of alternating EO prisms (long optical path length), with a pair of long electrodes across the prisms "flats". A controlling electric field synthesizes a piecewise gradient of index of refraction, effecting increasing deflection of a light beam as it propagates through the prism array. Elegant methods have been investigated for forming a continuous index gradient in a continuous block of EO material[41]. This analog catagory of either piecewise or continuous elements yields the same operational characteristics, and is identified by this author as *gradient deflection*[4,42]. A broad resource of linear solid electro–optic materials is available, including the two noted above, researched in 1943.

The digital form of electrooptic beam deflection may use either linear or quadratic EO materials. This is because it requires only binary EO changing of polarization, directed into passive birefringent switching of directon. A tandem array of n such switches provides 2^n output beam positions. One of the most successful digital deflectors tested[43] used nitrobenzene and calcite in 10 stages per X and Y axis to yield the highest resolution thus far, a 1024 x 1024-element TV display. This was reported in 1976 by the Philips Labs in Hamburg. Notably, Its lead researcher, U. Schmidt, expressed the values of nitrobenzene optical switching four years earlier[44].

During this extended period of activity at Philips, much work was done on digital deflection elsewhere, using solid linear EO elements such as KDP and KD*P. This work by many researchers, prior to the final release by Philips, is reviewed in an earlier referernce[13]. It resulted in performance which did not approach that of the above use of nitrobenzene EO material. This liquid exhibited no optical imperfections and, in direct contact with the surfaces, matched well the many tandem optical interfaces, including its calcite elements.

While currently, the solid EO materials are depended on for extremely broadband signal modulation, their use for beam deflection is notable for providing extremely fast positional error correction -- over distances corresponding to relatively few elements of resolution.

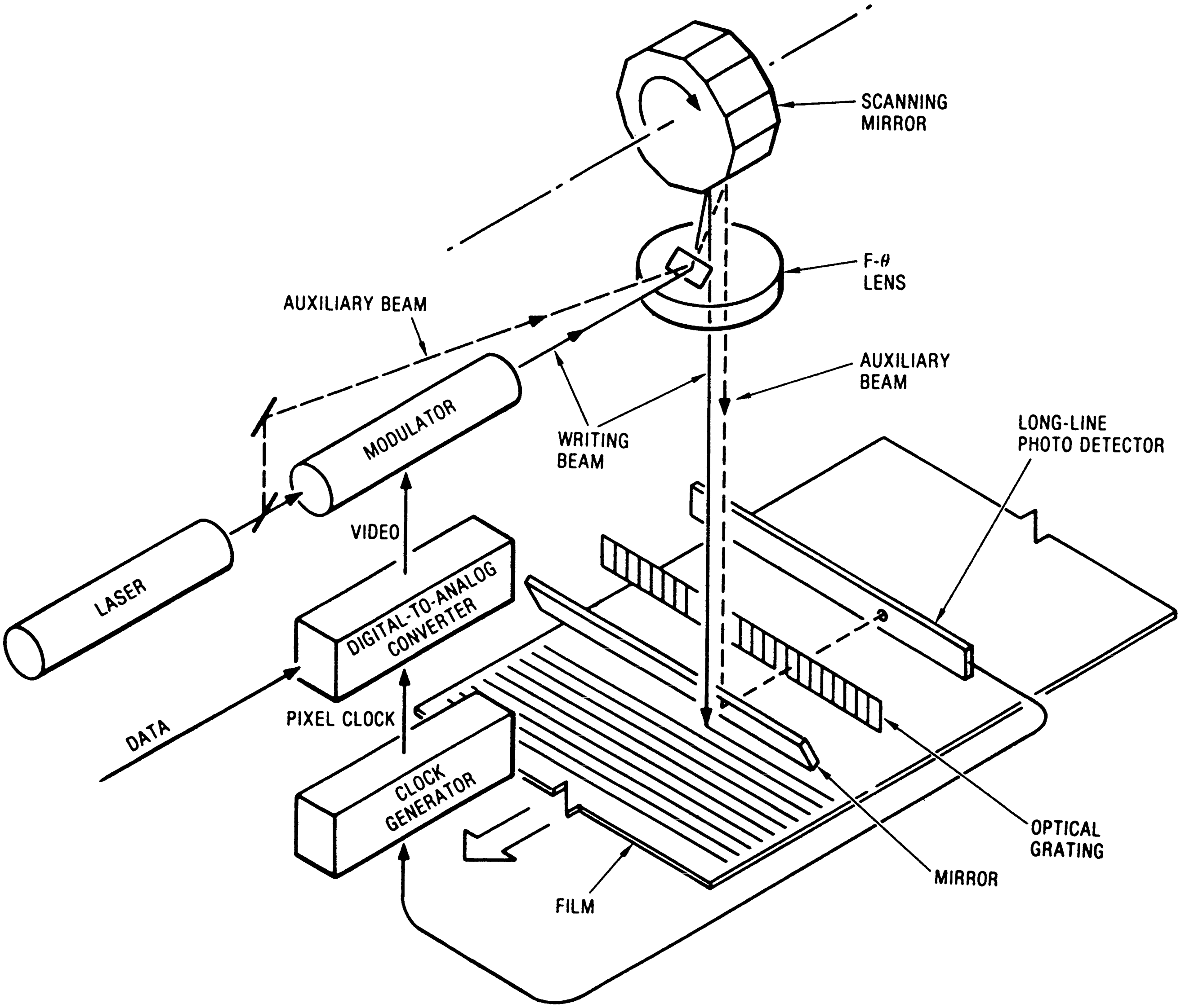
IX Control of Scanned Beam Misplacement

The prior section closed introducing the topic of beam position correction. In 1964, the electrooptic scanner was, in fact, one of the earliest described[10] for extremely fast beam repositioning. While it operates over a few resolution elements, it allows attacking a most insidious scanned defect: beam misplacement in the *cross-scan* direction; *banding.* This reqires precise matching of *adjacent* scan line spacing, line-after-line, "on the fly". Another function is straightening bowed scan line spacing. Electrooptic methods are especially useful for correcting these rapid errors, along-scan *or* cross-scan. If they change randomly, however, this requires provison for more complex real-time error detection and control.

In 1976 appeared what is now considered a classic method of equalizing precisely the *along-scan* beam position; even including random ones. Fig. 16 illustrates this published[45] use of an auxiliary unmodulated beam which travels along with the main beam and through its scanning and objective optics. This auxiliary beam is then directed through a precision grating. Its optical pulses are detected and used to trigger the extraction of pixels out of temporary store, thereby duplicating *along scan* the uniform spacing of the grating lines.

But, the insidious *cross-scan* errors persisted due, e.g., to scanner shaft wobble. The above electrooptic method is, however, not simple to implement. In contrast to that *active* method, a group of self-corerecting *passive* methods were developed[4], requiring no detection and feedback. The first such automatic control was from J. Fleischer, et al, in their 1973 system patent[46]. This now-familiar anamorphic technique, designed for the polygon, is applicable to mechanical deflectors in general, including holographic[9]. The input beam height on the deflector is reduced cross-scan only (typically with cylindrical optics). Following deflection, the beam is restored anamorphically to its original height, and focused on the image surface. A basic development of this process appears in prior references[4,14], which generalizes the concept to control the *magnitude* of correction.

In 1981, C. Kramer published his creative "outside the box" thinking[28] to yield the Bragg-angle holographic disc scanner. Reviewed comprehensively in



16 Auxiliary Beam polygon synchronization and scan linearization system. (Ref. 45, 1976).

an earlier reference[9], this simple–looking configuration provides favorable scan characteristics which, as noted in Section V, includes a reduced sensitivtiy to shaft wobble, with no additonal components or controls. This output angular stability is clarified with a novel analogy of the angular shift near the Bragg angle to that by a wedge prism nutating near its angle of minimum deviation[9,4].

Another method is identified as *Double Reflection*[4], in which the deflector which initiates the cross–scan error is reilluminated in opposing phase to null the error. Two types appeared in 1984. One[47] uses an *outside* roof prim to return the first–deflected beam for a second deflection at opposite phase. It works, with some limitations[4]. The other[48] is familiar for replacing the single–facet scanner (e.g., Fig. 11) with a pentaprism. It nulls *within* the prism. A stable and simpler double–reflector is the *Open Mirror* scanner[49] of 1990, serving the same function. These two "internal" double–reflectors were then extended with symmetric parts about the rotating axis to provide two scans per rotation: the pentaprism, to a pair of pentamirrors, as the *Butterfly* scanner[50], and the *Open Mirror scanner* to the *Paired Open Mirror* scanner[51]; extendable to four or more scans per rotation. In 1992, this configuration was developed further with nulled inertial deformation of its facets[52], thereby cancelling beam aberration at very high speed operation.

X Agile Beam Steering

Thus far, the technology discussed has been quite familiar to this audience, highlighting, primarly, an historical perspective and the paths of its develpment. We now enter a newer arena of low inertia beam positioning. Its R&D history goes back over four decades[13], and much revitalized work has been generated during the past 15 years[4]. However, little of this progress has illuminated the antennas of the Optical Scanning community until 1997, when it was introduced into our Optical Scanning conferences (SPIE'S Proc. Nos. 3131, 3787 and 4773.) The reason is similar to that noted at the end of Section III for Remote Sensing, and later for Reconnaissance and Wideband Recording; i.e., independent research communities. Since *Agile Beam Steering* represents another form of Low Inertia scanning, the two dominant newer disciplines for rapid beam positioning are identified in the Fig. 6 classification chart; under "NON-MECHANICAL" as *"Phased Array"*, and under "OSCILLATORY" as *"Microlens Array"*.

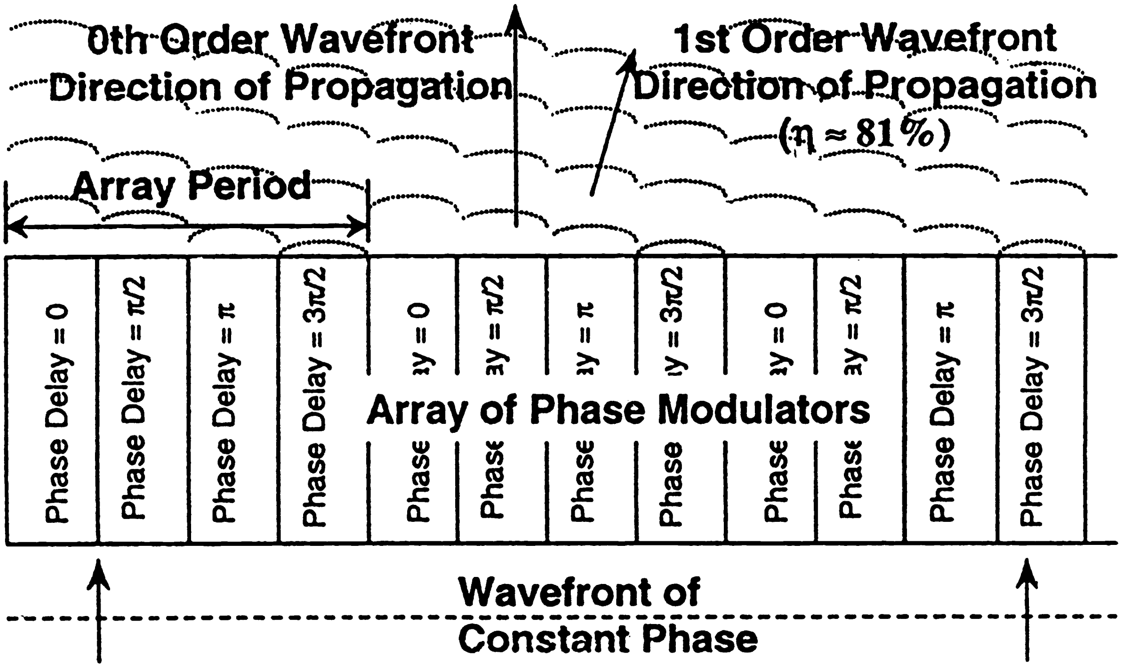
Xi Phased Array Development

The basis of this technology goes back to its development for radar[53] in which an antenna array is driven with controlled phasing to direct its radiation (or selectivity) pattern. Recall, too, the adaptation of this principle to the acoustical domain by the Zenith researchers[38] in 1966 (end of Section VII and Fig. 15): where, applying A-O scan, a phased array of acoustic transducers is programmed to shift the angle of its radiated acoustic wavefront (propagating through the A-O cell) such that the nominal Bagg angle is maintained.

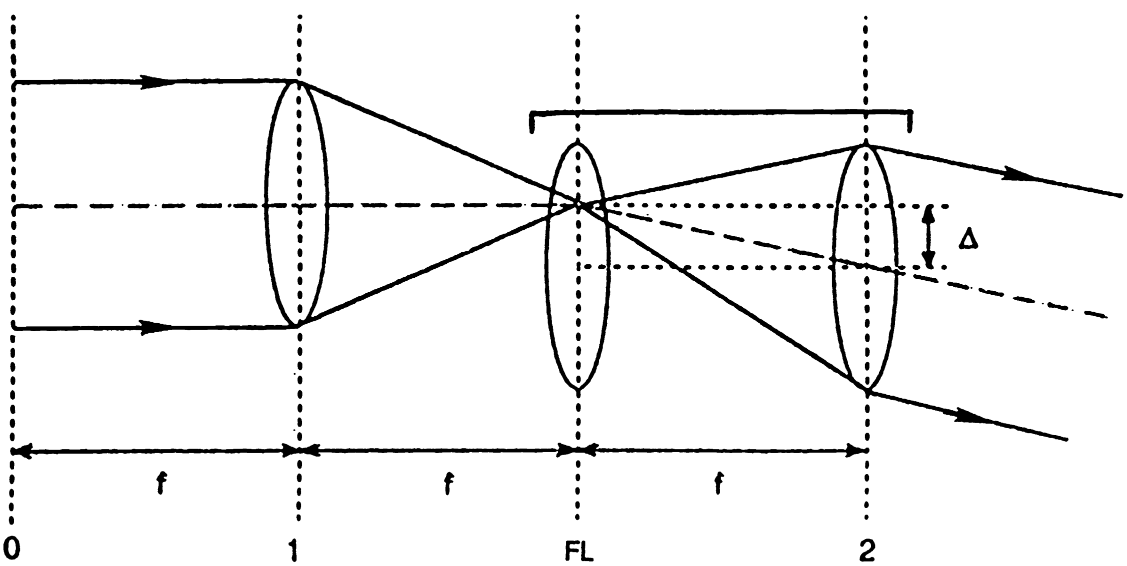
A schematic of the phased array is represented in Fig. 17. The full array of phase adjusters is segmented to form adjoining *(modulo 2π) array periods.* The full wavefront is formed from adjacent periodic increments which synthesize an efficient blazed grating. The adjacent output wavelets superpose to develop a contiguous desired 1st order wavefront. The phase adjusters may be formed of electrooptic variable phase retarders, as shown, or of mirrored "pistons" which require only fractional wavelength "microtranslation" for precise phase control.

Xii The Decentered Microlens Array

This approach, more recent than the above method, has gained substantial interest. It takes advantage of a well-appreciated optical effect: i.e., an afocal lens pair (e.g.. an optical relay, especially of short focal length lenses), will show significant beam angle misalignment for a slight transverse error of the lens axes. Effectively, a small transverse shift of one lens will generate a significant beam angle change. Ergo, beam scan by transverse shift of one lens with respect to the other. A linear array of small lens pairs, with "microtranslation" (in the array direction) of one set with respect to the other, forms a sensitive beam deflector. Fig. 18 indicates[53] that by adding a field lens (FL) at the common focal plane, all the flux entering Lens 1 illuminates Lens 2 during their relative displacement Δ.



17 Phased Aray Beam Steering. Phase delay modulator groups (e.g., 4 per 2π period) provide modulo 2π continuity. Superposed output wavelets form redirected wavefronts, simulating deflection by a continuous wedge, or by a blazed grating (Ref 4 and its References, 2002, 1999).



18 Beam Steering with Decentered Afocal Lens. Field Lens FL added to maintain filling of Lens #2 during displacement Δ. When such sets are miniaturized and assembled into a linear array, the distance Δ is reduced drastically, allowing rapid, low inertia beam positioning (Ref. 53, 1993).

Field lens FL and Lens 2 are coupled, to move jointly with respectd to Lens 1. It is noteworthy that such lens array systems also synthesize a blazed grating[53].

Further variations to this basic technology, along with expansions and comparisons of the above two methods, are presented in the referenced work[4].

XI Summary

This probing work explored the development of optical scanning, to document the basis of its historical perspective. Highlights were addressed with sufficient rigor to provide the listener/reader with a secure appreciation of the noblility and novelty of its pioneering background. Topics of advancement extended through the classics in the field, and concluded with an exposure to some of the most novel recognized research. Referencing of the work is extensive.

Not only is the progress represented, but some mutual relationships are illuminated; fitting into two general types: (1) similar creative thoughts are identified which reveal independent work along very similar lines, by potentially competing groups, within the same time frame; and (2) the complementary effect of independent work by one group which, had it been announced broadly, could have inspired an early start of (non–competing) development for a different purpose, by another group.

This brings to mind the virtue of the policy of some technical societies; most notably of the SPIE -- who provide rapid publication of their Conference Proceedings. We are rightfully proud of the 20 Proceedings and special issues of the SPIE Journal, in the field of Optical and Laser Scanning and Recording[54]. Since we're presenting history, this started in 1974 with SPIE Proc. Vol. No. 53!

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