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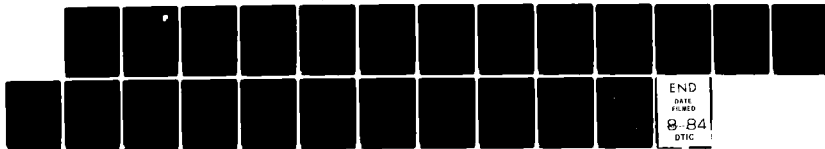
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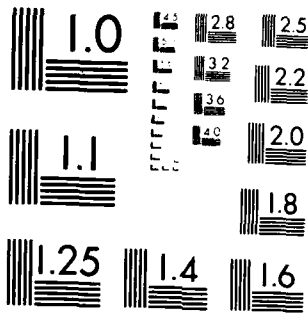
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In-House Report  
June 1984



DOPPLER AND THE DOPPLER EFFECT

Kurt Toman

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**ROME AIR DEVELOPMENT CENTER**  
**Air Force Systems Command**  
**Griffiss Air Force Base, New York 13441**

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Title of Report: DOPPLER AND THE DOPPLER EFFECT

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APPROVED:



JOHN E. RASMUSSEN  
Chief  
Propagation Branch  
Electromagnetic Sciences Division

APPROVED:



ALLAN C. SCHELL  
Chief  
Electromagnetic Sciences Division

FOR THE COMMANDER:



Carlo P. Crocetti  
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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>A summary is given of Doppler's life and career. He was born 180 years ago on 29 Nov 1803 in Salzburg, Austria. He died on 17 Mar 1853 in Venice. The effect bearing his name was first announced in a presentation before the Royal Bohemian Society of the Sciences in Prague on 25 May 1842. Doppler considered his work a generalization of the aberration theorem as discovered by Bradley. With it came the inference that the perception of physical phenomena can change with the state of motion of the observer. Acceptance of the principle was not without controversy. In 1852, the mathematician Petzval claimed that no useful |                       |   |

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scientific deductions can be made from Doppler's elementary equations. In 1860, Ernst Mach resolved the misunderstanding that clouded this controversy. The Doppler effect is alive and well. Its role in radio science and related disciplines is enumerated.



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PREFACE

Thanks are due to John E. Rasmussen and Gary S. Sales for their interest and support in this work. John Armstrong of the AFGL Research Library lifted my spirit with Cohen's 1939 Isis paper.

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DOPPLER AND THE DOPPLER EFFECT  
Kurt Toman, Propagation Branch  
Rome Air Development Center  
Electromagnetic Sciences Division  
Hanscom AFB, MA 01731

A summary is given of Doppler's life and career. The effect bearing his name is considered to be a generalization of the aberration theorem discovered by Bradley. With it came the notion that the perception of physical phenomena changes with the state of motion of the observer. Acceptance of the principle was not without controversy. In 1852, the mathematician Petzval claimed that no useful scientific deductions could be made from Doppler's elementary equations. In 1860, Ernst Mach resolved the misunderstanding that produced this controversy. The Doppler effect is alive and well. The roles it plays in radio science and related disciplines are enumerated.

Presented at the  
National Radio Science Meeting  
University of Colorado, Boulder, CO  
11-14 Jan 1984



## 1. Historical Background

The astronomer Olaf Roemer determined the velocity of light in 1676 from time interval measurements.<sup>[1]</sup> These intervals involved eclipses of the moons of Jupiter by the planet. Roemer made the important observation that the 42.5 hour orbital period of Jupiter's innermost moon Io measured between successive immersions and emersions from Jupiter's shadow was shorter when the Earth approached Jupiter and longer when it receded from Jupiter. In effect, Roemer used a Doppler method in determining the velocity of light.<sup>[2]</sup> In 1727, James Bradley attempted to use the earth's orbit as a baseline for determining the distance to the nearest stars by triangulation.<sup>[3]</sup> Though failing in this effort, Bradley discovered the phenomenon of aberration; that is, the elevation angle at which a star is seen varies with the relative speed of the observer.

In both studies the orbital motion of the earth played an important role. In Roemer's study the time intervals shortened when the observer approached Jupiter and lengthened when he receded. In Bradley's study, the elevation angle to a star changed with the observer's speed. While Doppler barely mentioned Roemer's work in his 1843 publication<sup>[4]</sup>, he cited Bradley's aberration theorem claiming that his own study to be a generalization of Bradley's discovery. Doppler stated his principle in simple terms: A boat moving towards approaching water waves shortens the perceived wave periods; moving with the waves lengthens them. He postulated that the colors of stars are the result of motion between them and the earth and asserted that "if the orbital speed of the earth would be ten times its actual value, all fixed stars in the eastern part of the ecliptic would, without exception, appear blue or green, those in the west orange or red".

## 2. Doppler's Life and Career

Christian Doppler's grandfather was a master stonemason. In 1791 he moved from Himmelreich, Bavaria to Salzburg, Austria, No. 1, Makart Square. A year later Doppler's father took over his grandfather's business. Christian Doppler was born in his grandfather's house on 29 Nov 1803. As the second son, he was expected to become a stonemason like his father. Because of weak health he stayed longer in elementary school and had to repeat classes. He then transferred to Linz, where he attended the fourth class of high school and was about to enter the business of his father. His uncle and Professor Simon Stampfer both recognized Doppler's superior talent and recommended that he be allowed to further his education. His father agreed, and in Oct 1822 Doppler went to Vienna where he took courses in mathematics, physics and mechanics at the Polytechnic Institute. He remained there until January 1825 and distinguished himself through "diligence and outstanding behavior".

Although 22 years of age, Doppler still had to complete his high school studies in order to gain admission to the University. In Salzburg, he was privately tutored and completed a six year course in 2 1/2 years and classes in philosophy (Grades 11 & 12) in two years. Meanwhile, he tutored others in mathematics and physics, supported his mother and needy sisters, studied French, Italian and English and learned accounting in a trade shop. In 1829 he returned to Vienna where for four years he held the position of assistant to Hanschl in advanced mathematics at the Polytechnic Institute. During the years 1829-1833 he published papers in mathematics and physics including "On the theory of parallels", "Convergence of an infinite logarithm sequence", "Likely cause of electrical stimulation through friction". He decided to devote himself fully to a career in science. In September 1833 Doppler left the Polytechnic Institute

and applied for vacant teaching positions for which he had to pass special examinations. He was not successful. His bitterness made him decide to emigrate to America. He went to Munich to contact the American Consul. At the same time, he received several job offers. One was a professorship in mathematics and accounting at the City High School in Prague, and another to teach higher mathematics and physics at a High School in Bern. For patriotic reasons he accepted the former offer and in 1835 he moved to Prague. The following year he married Mathilde Sturm, the daughter of a gold and silversmith master from Salzburg. He was active at the City High School for two years, then became a substitute professor, and in 1841, a full professor at the Technical Institute in Prague. In the proceedings of the Royal Bohemian Society of the Sciences, (which he had joined in 1840) he published several articles including one on the colored light of double stars. In 1847, Doppler became a Professor of Mathematics and Physics in Schemnitz (Banska Stiavnica). During his short stay there, he received an honorary doctor's degree in philosophy from Prague, and the Royal Academy of Sciences in Vienna awarded him full membership. The following year, in October 1848, he became a professor at the Polytechnic Institute in Vienna and succeeded his former teacher Stampfer to the chair for practical geometry. In 1850 the University of Vienna was authorized to establish a physics department whose main purpose was to train high school physics teachers. Doppler became the head of this department with the rank of "ordinary" professor and served on the science examination commission for physics teachers. At age 47 he had achieved a highly honored position. His teaching load and the technical efforts weakened his body, but not his mind. He developed a lung disease. In autumn of 1852 he requested sick leave, and following the advice of his doctor,

went to Venice to recover. Sadly, on 17 March 1853 he died in his wife's arms leaving behind five young children. He lies buried in the cemetery of Venice where a monument was erected in his honor.

Doppler's papers were published in various scientific journals: Viennese Polytechnical Volumes; Hessler's Encyclopedic Magazine; Baumgartner's Magazine for Physics and Mathematics; Poggendorff's Annals of Physics; Proceedings of the Royal Bohemian Society of Sciences, and the Records of the Imperial Academy of Sciences in Vienna.<sup>[5]</sup> Because of the fast growth in science, many of Doppler's treatises have lost their significance. Only his principle of the Doppler effect has gained in importance and continues to do so.

### 3. The Principle

The Doppler effect is a change in perceived frequency caused by motion of either the source or the observer. In a different way it could be said that the Doppler effect is the change in the apparent time interval between two events that arises from the motion of an observer taking into account the finite velocity of transmission of information about these two events.<sup>[2]</sup> Doppler stated his principle in 1842, first for sound and then for light. He applied his principle to the perceived colors of stars along their line of sight velocities. In his description of the effect for light, Doppler referred to the original vibration hypothesis according to which the perception of color is an immediate consequence of the time intervals between regular, successive and recurrent pulsations or wave crests of the ether. Therefore, anything that changes the time interval between pulsations must necessarily be associated with a change in perceived color. Doppler found it noteworthy that in the study of light and sound, and in wave theory in general, not enough attention had been paid to the subjective conditions (as opposed to objective conditions) which really determined the color and intensity of a light sensation or the

pitch and intensity of sound. As long as the source of waves and the observer remained stationary at their original locations, it was clear that the subjective and objective determinations of color (light) or pitch (sound) coincided.

This would not continue to be so, however, if either the source or the observer or both move toward or away from each other. Doppler expressed this as follows:

"Assume that either the observer or the source or both simultaneously change their location, receding from or approaching each other with a speed which is somewhat comparable to that of the wave. There is no doubt that the path length and the time interval between two successive wave crests shortens for an observer that moves against the wave motion, and becomes longer if he moves with the wave motion."

Doppler derived two simple equations describing the change of the time intervals depending on whether the source moves and the observer is stationary or whether the observer moves and the source is stationary. Doppler's formula, restated in a simplified form, is<sup>[6]</sup>

$$f' = f \frac{c \pm u}{c \mp v} \quad (1)$$

where  $f$  is the frequency of the source,  $f'$  is the frequency perceived by the observer, and  $c$ ,  $u$  and  $v$  are respectively the velocity of the wave in a stationary medium and the velocities of observer and source with respect to this medium.

If one assumes that the speed of the source  $v = 0$  one obtains for the perceived frequency of sound

$$f' = f \frac{c \pm u}{c} = f(1 \pm \frac{u}{c}) \quad (2)$$

In the limit  $u=c$ ,  $f' = 0$  for the receding observer. For the approaching observer,  $f' = 2f$ . In the former case sound waves do not reach the observer and the sound is not perceptible. In the latter case, the pitch moves up by an octave.

If one assumes that the observer is stationary, i.e.  $u=0$ , one obtains

$$f' = f \frac{c}{c \mp v} \quad (3)$$

where  $v$  is the speed of the source. In the limit  $v = c$ ,  $f' = f/2$  if the source is receding, and  $f' = \infty$  if the source is approaching. Here, for the receding source the pitch of a tone moves down by an octave, while for an approaching source all wave crests arrive at the observer at the same time producing a sound of infinite pitch which cannot be heard.

At the conclusion of his 1843 paper Doppler acknowledged that Olaf Roemer taught us a value for the velocity of light, and that many years thereafter it was a general opinion that "no bodily motion in the heavens could compare in magnitude with that of light". He also stated that, "there was Bradley who gave us the aberration phenomenon". Doppler went on to say that "if the orbital speed of the earth (4.7 miles/second with 1 mile = 6.38 km) produces an aberration of 20 seconds of arc, why should not a much larger speed cause a change in color and intensity of light". In fact, Doppler does not speak of "a possibility of such large speeds but rather of a necessity".

The verification of Doppler's principle for sound followed in 1845 when the Dutch physicist Buijs-Ballot placed musicians with excellent pitch perception along the railroad tracks between Utrecht and Maarsen. They estimated for approaches and recedes the pitch of the tone a horn player produced on board a moving train. The speed of the train was determined with two chronometers and a marked 100m distance along the track.<sup>[7]</sup> Among the astronomers of his time,

only Benedetto Sestini from the Collegio Romano believed in Doppler's ideas on the color of stars. Sestini claimed that he had noted colour changes in binary stars.

The laboratory demonstration of Doppler's effect for light was, of course, much more difficult than for sound, but it was carried out in the year 1900 by Belopolsky.<sup>[8]</sup> In the following year, Michelson, without calling Doppler's principle in question, suggested that the change in perceived frequency may be caused not only by motion of the source or the observer, but also by a rapid alteration in the density of the medium crossed by the light ray.<sup>[9]</sup>

#### 4. Controversies

##### a. Color of Stars

Two controversies evolved concerning Doppler's work. His principle was challenged by Buijs - Ballot and Petzval. Although Buijs-Ballot had verified Doppler's principle for sound, he rejected the application of the principle to explain the color of binary stars on the following grounds:

1) The human eye does not have the sensitivity to color that Doppler believes.

2) A change in color due to the motion of a star cannot occur because should a part of the red spectrum disappear, ultraviolet reserves would appear; similarly, should a part of the violet spectrum disappear, ultrared reserves would appear.

3) Known velocities of celestial bodies were about  $2 \times 10^{-4}$  of the velocity of light, too small for the eye to perceive color changes resulting from motion.

Nevertheless, seven years later in 1852 Doppler reaffirmed his conviction that the color of stars would aid in determining the trajectories of

celestial bodies. This conviction was based on his belief that the spectrum is a band of frequencies terminating at the red and violet, so that a receding motion of the source would shift the violet to the blue where the observed spectrum would end.<sup>[6]</sup> It is interesting to note that the concept of the expanding universe, deduced from observing increasingly remote celestial objects by means of the Doppler effect, agrees with the color changes Doppler originally anticipated for his stars.

Doppler tied his principle to the longitudinal theory of light waves, assuming an ether like Huygens did but with the difference that the ether's individual particles are much finer than those of matter and could not be weighed. Although the transverse theory of light waves had been formulated by Young<sup>[10]</sup> in 1817, Doppler, while acknowledging in 1842 its success, remarked<sup>[4]</sup> "that to believe this theory requires a lot of faith". Later, however, Doppler started wondering about whether his principle would be compatible with the transverse theory of light waves.<sup>[11]</sup> His doubts were dispelled by the Weltpriester Bolzano.<sup>[12]</sup>

#### b. Petzval's challenge

The validity of the general Doppler principle was not universally accepted by men of science, the chief antagonist being Petzval. Petzval was born on 6 January 1807 in Szepes Bela, Hungary, the son of an elementary school teacher. At age 30, he became professor of mathematics and mechanics at the University of Vienna. He made significant contributions to the development of optical lenses for telescopes, microscopes and binoculars. At one time, he was assigned ten military gunners to help with computations. The entire British Navy was eventually supplied with his binoculars. When thieves stole a large manuscript



on optics from his apartment, he retreated to an abandoned monastery. From this domicile he rode daily on an arabic horse to the University to give his lectures. Petzval died in Vienna, an almost forgotten man, on 17 Sep 1891.

It was shown earlier that according to Doppler, "the received frequency reaches infinity if the observer is at rest and the source moves with the wave speed in the medium". If the source moves faster than the wave speed, the received frequency would be negative. That cannot be since the medium would be dragged along by the moving source and waves would form in the direction of motion such that the received frequency would have a finite, positive value.

Doppler made the error in believing that his elementary formulas yielded exactly the magnitude of the actual frequency change. He overlooked the influence of moving bodies on the medium itself and omitted considering the medium in his formulas. Although this error had probably no bearing on the optical phenomenon, it could not be passed over lightly because Doppler did introduce for his principle a material ether. He considered his equations as representing not only the pure principle but also the physical event. This identification allowed Petzval<sup>[13]</sup> to prove Doppler's formulas to be in error relative to the physical event, but Petzval extended his criticism to the principle itself.<sup>[14]</sup>

What was Petzval's argument which surfaced about 10 years after Doppler's presentation in 1842? How was it resolved? Let us first state Petzval's law: If a source is located in a medium and all particles constituting the medium have identical velocity vectors and the required continuity condition of the flow is satisfied for all points at rest with respect to the source, then the received frequency equals the transmitted frequency irrespective of the physical properties and state of motion of the medium.<sup>[14]</sup> While Doppler acknowledged and appreciated the value of Petzval's law, he rejected the claim for its broad applicability.

Petzval, in turn, rejected the correctness of Doppler's principle which was Petzval's mistake and made him the aggressor in this dispute. Petzval rejected popular views as providing no cognitive values for scientific understanding. He also claimed that to discover a principle of nature, one must start from differential equations.

Addressing the dispute between Doppler and Petzval, a series of articles on the subject of change of pitch and color through motion were published by Mach.<sup>[15]</sup> It became clear that Petzval's rule, which he himself elevated to the rank of a principle, was valid only when source and observer are at rest with respect to each other. Doppler's principle, on the other hand, applied to the case of a change in frequency as a result of relative motion between source and observer with the state of rest being only a special case.

#### 5. Modern Applications

Wide applications of the Doppler effect to fields other than astronomy emerged only since the Second World War. Its use in navigation, missile and satellite tracking, radar, remote sensing, etc. is steadily growing. The Doppler effect applies to any periodic process.

One recent development is a Doppler Acoustic Sounder.<sup>[16]</sup> The device uses three antennas to transmit pulses of sound which are reflected back to the antennas from turbulence in the air. The frequency of the echo shifts with the speed and direction of the wind, which may be computed and displayed on a video screen. The wind is made "visible" by converting the numerical data into colors. This system has been used at factories to monitor the dispersal of pollutants and at airports to test wake turbulence and wind shear.

A second example involves remote satellite measurements of atmospheric winds by scatterometers.<sup>[17]</sup> Bragg scattering of radar microwaves from centi-

meter-long surface ocean waves is proportional to the amplitude of these waves, which in turn depends on the wind just above the ocean surface. This backscatter is not isotropic, and therefore wind direction can be deduced from a comparison of backscattering from different directions. The Seasat scatterometer uses four vertically and horizontally polarized fan-beam antennas oriented in specified directions relative to the satellite's direction of motion, producing an X-shaped pattern of illumination on the earth. Returns from different ranges are separated by their differing Doppler shifts. Radar cross sections are determined for each resolution cell and normalized to a perfectly conducting reflector perpendicular to the radar beam filling the entire antenna pattern. A component windspeed is calculated with a look-up table relating radar cross section to windspeed at 19.5m above the surface. The same is done with the orthogonally viewing scatterometer antenna. The resulting wind speed components can be related to a vector wind velocity.

A third example is the monitoring of the ionosphere by vertical and oblique high-frequency ionospheric soundings. This is illustrated in Figure 1. Over a 24-hour period, signal amplitudes and Doppler Frequency variations at two operating frequencies originating from the Time Station CHU in Ottawa, Canada were simultaneously received and recorded at a field site in Bedford, MA, separated from the transmitter by a distance of 480 km. The upper record illustrates the signal behavior for a carrier frequency of 7.335 MHz, the lower sample for 3.33 MHz. In each record, the signal amplitude in microvolts is shown at the top while Doppler shifts associated with time variations of ionospheric phase path are shown at the bottom. The horizontal lines occur at 0.5 Hz Doppler frequency intervals. For 7.335 MHz, a 0.5 Hz Doppler shift corresponds to a time rate of

change of phase path equal to 20.44m/s; for 3.33 MHz, a 0.5 Hz shift corresponds to 45.04 m/s. A relatively stable frequency trace is seen for the 3.33 MHz carrier between 0800 and 1600 EST; at 1630 EST, a solar flare effect commenced, producing wide variation in rate of change of the phase path.

Other applications involve the areas of Doppler navigation (NAVSAT, NAVSTAR), adapting HF communications to circumventing the undesired presence of Doppler spread, which contributes to frequency uncertainty in signal transmissions, semi-active radar guidance in a missile-target intercept-geometry, tracking of meteors, hydrometeors, insects, birds, development of circuitless electron beam amplifiers, etc.

#### Conclusion

While Doppler's principle had a controversial beginning, the applications to astronomy, radio science, navigation, communication, radar detection and probing are impressive and growing. Doppler was the first person to postulate changes in perceived frequency due to relative motion between source and observer. Olaf Roemer, however, opened the door for Doppler's discovery not only by determining that light had a finite velocity, but in addition by noting that the recorded periods of revolution of Jupiter's innermost moon were shorter when the Earth approached Jupiter and longer when it receded from Jupiter.

In the development of ideas on time, space and motion, Doppler's contribution links the early findings of Roemer and Bradley with those of Lorentz and Einstein.

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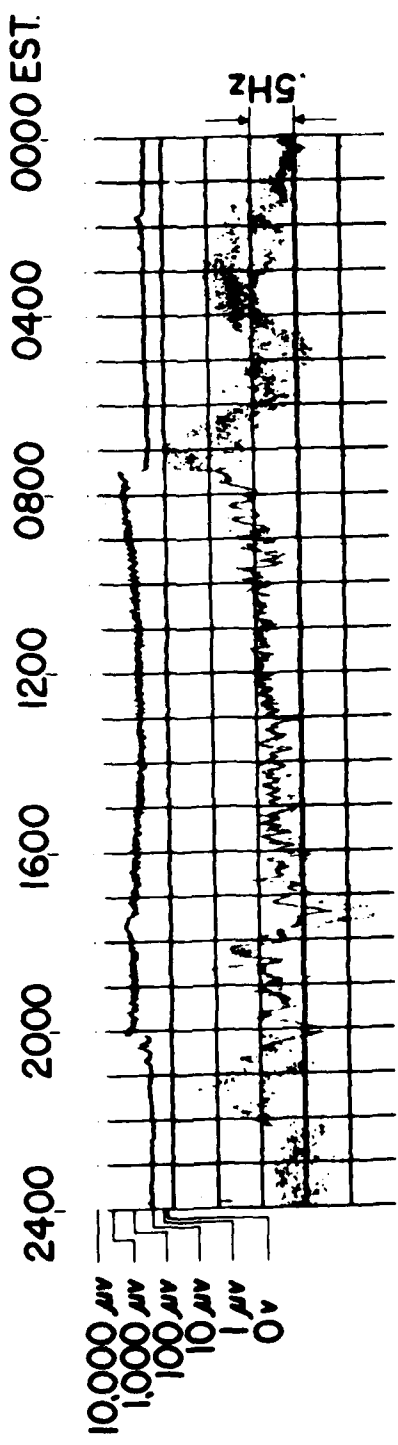
### HISTORICAL SUMMARY

(From the "instantaneous" propagation of light to a finite speed of light; from discovery to some applications of the Doppler effect)

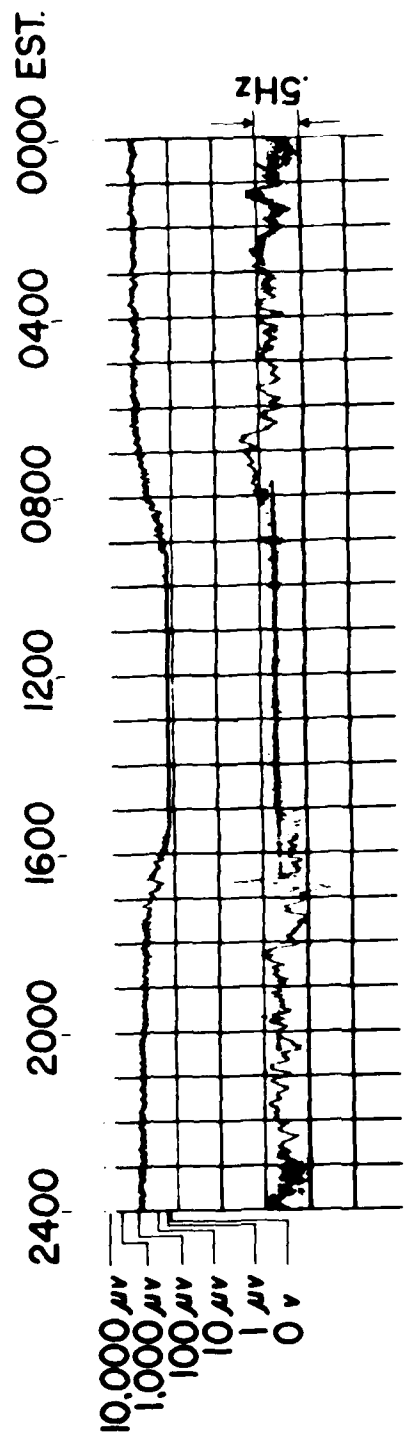
|      |   |                       |                        |
|------|---|-----------------------|------------------------|
|      | Believed Speed of light is finite.  | Empedocles            | 492-432B.C.            |
|      | Believed light propagates "instantaneously".  | Aristotle             | 384-322B.C.            |
|      | Light propagates "instantaneously"; with "proof"!   | Heron of Alexandria   | ? - 62A.D.             |
|      | Felt more than he believed finite velocity of light.  | F. Bacon              | 1561-1626              |
|      | Designed first successful astronomical telescope; proposed experiments to determine speed of light.                                   | G. Galilei            | 1564-1642              |
| 1621 | Believed light propagates "instantaneously".<br>Discovery of law of refraction.   | J. Kepler<br>W. Snell | 1571-1630<br>1591-1626 |
|      | Believed light propagates "instantaneously".  | R. Descartes          | 1596-1650              |
| 1650 | First discovery of a double star.   | G. Riccioli           | 1598-1671              |
| 1676 | Discovery/determination of <u>finite speed of light</u> .   | O. Roemer             | 1644-1710              |
| 1678 | Light is a longitudinal wave phenomenon.  | C. Huygens            | 1629-1695              |
| 1727 | Discovery of <u>aberration</u> phenomenon.  | J. Bradley            | 1692-1762              |
| 1817 | Light is a transverse wave phenomenon   | T. Young              | 1773-1829              |
| 1818 | Huygens secondary wavelets combined with Young's idea of interference.  | A.J. Fresnel          | 1788-1827              |
| 1842 | Discovery of <u>Doppler principle</u> ; associated with longitudinal theory of light.   | C. Doppler            | 1803-1853              |
| 1844 | Believed to have observed color changes in double stars; supported Doppler's idea that color of stars changes due to relative motion. | B. Sestini            | 1816-1890              |
| 1844 | Doppler principle valid for transverse theory of light.   | B. Bolzano            | 1781-1848              |
| 1845 | Doppler principle verified in acoustics.  | C.H.D. Buijs-Ballot   | 1817-1890              |
| 1848 | Doppler effect applies to spectral lines but not to color.  | A.H. Fizeau           | 1819-1896              |

|               |   |   |                         |
|---------------|---|---|-------------------------|
| 1852          | Negation of Doppler's principle.  | J. Petzval                                    | 1807-1891               |
| 1859          | Discovery of spectroscopic technique.   | R. Kirchhoff<br>R. Bunsen                     | 1824-1887<br>1811-1899  |
| 1860/62       | Resolution of Petzval-Doppler Controversy.  | E. Mach                                       | 1838-1916               |
| 1863          | First application of Doppler principle to astronomy.  | P.A. Secchi                                   | 1818-1878               |
| 1864          | Unification of light and electricity.   | J.C. Maxwell                                  | 1831-1879               |
| 1868          | Detection of red-shifted H-line<br>(Earth recedes from Sirius with 47 km/s).                                    | W. Huggins                                    | 1824-1910               |
| 1871          | Doppler-shifted spectral lines measured at limbs of sun.  | H.C. Vogel                                    | 1841-1907               |
| 1881          | Interferometer experiment for speed of light and ether.   | A.A. Michelson                                | 1852-1931               |
| 1887          | Repeat of speed-of-light experiment   | A.A. Michelson<br>E.W. Morley                 | 1852-1931<br>1838-1923  |
| 1889          | Determination of orbital velocity of Venus.   | H.C. Vogel                                    | 1841-1907               |
| 1889          | Existence of electromagnetic waves verified.  | H. Hertz                                      | 1857-1894               |
| 1900          | Doppler principle for light verified in the laboratory.   | A. Belopolsky                                 | 1854-1934               |
| 1901          | First transatlantic radio signal.   | G. Marconi                                    | 1874-1937               |
| 1904          | Developed transformations that made Maxwell's equation<br>invariant to all uniformly moving inertial<br>frames. | H.A. Lorentz                                  | 1853-1928               |
| 1905          | Doppler principle tested in the laboratory on canal<br>rays observing Hydrogen Palmer-line broadening.          | J. Stark                                      | 1874-1957               |
| 1905          | Formulation of special theory of relativity.  | A. Einstein                                   | 1870-1955               |
| 1919          | Discovery of recession of galaxies.   | E.P. Hubble                                   | 1889-1953               |
| 1925          | First radio echoes from ionosphere using continuous<br>wave technique.  | E.V. Appleton<br>M. Barnett                   | 1892-1965               |
| 1926          | First radio echoes from ionosphere using pulse method.  | G. Breit<br>M.A. Tuve                         | 1899-1981<br>1901-1982  |
| 1949          | Determination of meteor speed with radio Doppler method.  | D.D. Cherry<br>C.S. Shyman                    |                         |
| 1950          | Studies of upper atmosphere winds by radio echoes from<br>meteor ionization trails.                             | L.A. Manning<br>O.G. Villard<br>A.M. Peterson | 1923-<br>1916-<br>1922- |
| 4 Oct<br>1957 | Doppler tracking of radio signals from Sputnik begins.  |   |                         |





CHU 7.335 MHz AFCRL 1 FEB. 1969



CHU 3.330 MHz AFCRL 1 FEB. 1969

