THE PFUND SKY COMPASS

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The discovery of basic principles has seldom been accompanied by the vision of the use to be made of the knowledge acquired. In fact, many of the principles so important to modern living were first considered purely theoretical and devoid of any practical value, even by their discoverers.

When Benjamin Franklin brought lightning from the clouds down his kite twine, could he foresee the myriads of uses to which electricity would be put two centuries later ? When Marie Curie discovered radioactivity, could she imagine the atom bomb and the impact of nuclear physics on the world today ?

Polarization of light may never exert the far-reaching influence on civilization that electricity and radioactivity have, but when one Erasmus Bartholimus first observed polarization of light in Copenhagen in 1669, could anyone suppose that nearly three centuries later it would be the means of guiding monstrous mechanical man-carrying birds across trackless polar wastes? Yet the Pfund Sky Compass, depending for its operation on the polarization of sunlight, is doing precisely that. But why is it needed ? How did it come into being ? How does it operate ? What are its limitations ? Does it work ? Let us consider these questions one at a time.

NEED FOR SKY COMPASS

One of the fundamental requirements of navigation is the determination of direction. The direction of Point B from Point A is easily determined if the positions of the two points are known. This is usually done by measurement directly on the chart. Thus, if a person wishes to go from Point A to Point B, he can easily enough find out what direction he must go to reach his destination. But to follow the desired direction is another matter.

The problem of controlling direction of motion is customarily solved by means of a compass. In aircraft this instrument provides an indication of direction by virtue of the attraction of the earth's magnetic poles for the aviator's magnetized compass needle. Aboard ship direction is controlled either by the magnetic compass or by utilizing the directional properties of a pendulous gyroscope or similar device.

But the magnetic compass makes use of the horizontal intensity of the earth's magnetic field, and as one approaches the magnetic poles, this becomes progressively weaker. Over a large part of the polar regions the magnetic compass is unreliable. Even when the directive force is sufficiently strong, the accuracy of the magnetic compass is reduced by uncertainty as to the amount of variation and large changes in its value during various hours of the day, as well as the possibility of changing deviation, and the disturbing effects of intense magnetic storms.

As the geographical pole is approached, the directive force of the marine gyro compass becomes progressively less until at the pole it disappears altogether.

Aviators have resorted to a *directional gyro*. This instrument continues to indicate the direction for which it is set, for a relatively short time, but it is light and easily diverted from its original direction, so that it has the disconcerting habit of wandering off for an unpredictable amount and direction. At times its operation may be reasonably predictable and steady, but at other times it is quite erratic, and there is usually no warning as to its intentions. Despite its weakness, this device has proved very useful when used in conjunction with some other means of determining direction. The independent means is used for setting the directional gyro initially and checking the accuracy of its setting several times per hour.

The directional gyro is usually set or checked by a magnetic compass, if available, or by astro compass, a device for determining the direction or azimuth of a celestial body toward which it is pointed by providing a mechanical solution of the navigational triangle. Thus, an astro compass is useful, but only when a celestial body is visible.

For an observer at the geographic pole celestial bodies circle the sky without changing altitude, except as the declination changes. Thus, stars remain at essentially the same altitude. The sun rises once a year and the moon once a month. When the lower limb of the sun touches the horizon late in September (northern hemisphere), it is still more than 32 hours before the entire sun drops out of sight for its six months stay south of the horizon, which coincides with the equator. While the sun is setting, it makes a trip and a third around the horizon, covering more than 480° in azimuth.

As the last thin bright rim drops out of sight, the sun continues to circle the sky *just below the horizon.* Eight days later it reaches a distance of 3° below the horizon and the brightest stars begin to appear faintly in the sky. In another eight days civil twilight ends and the first sensation of gathering darkness begins to set in.

But during those first eight days when no celestial bodies are available unless the moon or a bright planet happens to be above the horizon, how is the navigator deprived of the use of his astro compass and with an unreliable magnetic compass and no gyro compass, to determine direction ? All directions at the north pole are south, but selection of the wrong south can be disastrous.

The conditions described exist only at the pole itself, but as the pole is left behind, the situation changes slowly. Anywhere north of Alaska the twilight lasts for several hours and the motion of an aircraft, usually exceeding the rotational velocity of the earth, can easily prolong the effect almost indefinitely.

Before development of the Pfund Sky Compass, twilight was the blind spot of polar navigation, the one situation most dreaded by the high-latitude navigator. The sky compass operates best during this period.

ORIGIN OF SKY COMPASS

Although polarization of light was discovered as early as 1669, as pointed out above, it was not until 1936 that a scientifically curious physicist at Johns Hopkins University in Baltimore, the late Dr. A.H. Pfund, developed a "half-shade apparatus" which revealed strikingly the polarization of light of the blue sky.

Late in 1944, Dr. Pfund, with renewed curiosity as to the possibilites of his "half-shade apparatus" constructed a crude model to observe the polarization effect in more detail. By means of this device he was able to locate the sun by altitude and azimuth with surprising accuracy, *even when the sun was somewhat below the horizon !*

The device became a curiosity to show visitors. But in those busy war years visitors—nearly always members of the official family in Washington—were too busy with practical matters to spend much time with curiosities, and the device was gradually pushed farther back on the shelf and began to gather dust.

Then, in January of 1947, Commander T.D. Davies, USN, who had recently commanded the *Truculent Turtle* on its historic flight from Australia to Ohio, and who was a man with imagination and a full appreciation of the problems of polar navigation, heard of the device by pure chance and was definitely interested. A quick trip across the 40 miles from Washington to Baltimore brought him to the laboratory of Dr. Pfund. One demonstration satisfied him that he had made a great find. Here at last was a real possibility for solving the twilight riddle. Here was the means of determining both altitude and azimuth of the sun during the long polar twilight. Perhaps only the azimuth could be determined with practical accuracy, since the accuracy requirements are much higher for altitude than for azimuth. But this would be good enough, for, if successful, the method would fill the one most pressing need of the polar navigator.

A short time later the National Bureau of Standards, at the request of the U.S. Navy Bureau of Aeronautics, undertook development of an instrument to determine direction, based upon the work of Dr. Pfund. There the compass came into being under the direction of Dr. W.G. Brombacher, who first applied the name "sky compass". Four of the instruments in experimental form were made and turned over to the Navy.

OPERATION

The operating principles of the sky compass are surprisingly simple. The direct rays of the sun contain vibrations in all directions, and are said to be *unpolarized.* As the sunlight enters the earth's atmosphere, part of it is scattered, giving the sky its characteristic blue appearance. This scattered light is *plane polarized.* That is, its vibrations are all in a single plane perpendicular to the direct ray from the sun. This means that if the sun were on the horizon due east or west of an observer, the plane of polarization would be vertical through the observer's zenith and the north and south points of the horizon. As the sun rose in the sky or sank below the horizon, the plane would tilt, always being perpendicular to the line from the observer to the sun. The sky compass determines this plane and the vertical plane through the observer and the sun. It is this second plane, called the *azimuth plane,* which is of particular interest to the navigator, since this gives him the direction of the sun.

The optical system of the sky compass is very simple and makes use of a principle known for a long time. It consists of a circular sheet of polaroid about 4 1/2 inches in diameter, on which is mounted a piece of cellophane of selected thickness. This is called an *analyzer.* The polaroid is similar to that used in certain sun glasses. The cellophane is cut in the shape of a many-sided star about one-third the diameter of the polaroid. A piece of clear material is placed over the cellophane for protection.

Plane polarized light can be resolved into two components perpendicular to each other. As the light strikes the polaroid, one component is absorbed and the other passes through. If the polaroid is rotated around an axis parallel to the beam of light, the relative magnitudes of the two components vary, so that the polaroid appears alternately bright and dark, making the change from one extreme to the other each 90°. That is, the complete cycle from bright to dark to bright again takes place in a rotation of 180°, or from the plane of polarization back to the same plane again. Thus, the bright and dark positions indicate the location of the plane of polarization and the azimuth plane.

The polaroid alone would thus determine the direction of the sun, but the points of maximum and minimum brightness are not sharply enough defined for navigational purposes.

When polarized light enters the cellophane, one component passes through unchanged and the other is changed in phase by 180° without change in amplitude. The result is the same as would be obtained by rotating the plane of polarization, thus shifting the points of maximum and minimum brightness. Thus, as the analyzer is rotated, the polaroid appears alternately brighter and darker than the cellophane. The two appear equally bright when the optical axis of the cellophane is in the plane of polarization, and equally dark when 90° from this plane. This results in there being four *match points* 90° apart. Since one part is becoming brighter while the other part is becoming darker, these match points can be distinguished with considerable accuracy.

The remainder of the instrument consists of a suitable frame, a 45° mirror under the analyzer to permit a horizontal view by the user, leveling screws, spirit levels, and suitable graduated scales. A clock is attached so that once the instrument is set, it remains oriented for time as the sun changes position.

To use the instrument, it is necessary only to orient it properly in the aircraft, set in local apparent time (after the first observation this will be already set in), turn the analyzer until the proper match point is obtained, and read the direction of the sun or the heading of the aircraft. A reading can be made in a few seconds.

A possible ambiguity of 90° or 180° exists, but relative sky brightness makes this easy to resolve.

LIMITATIONS

When an observation is made by sky compass, the instrument is first carefully leveled, so that the line of sight will be directed at the zenith, and *not the sun.* The light in the sky is only partly polarized. In the plane of polarization the percentage of polarized light is high, decreasing gradually as the angular distance from this plane becomes greater. At about 50% the percentage drops off rapidly. Since the sky compass depends for its operation on polarized light, the greater the percentage of such light entering its optical system, the more sensitive the instrument. Also, at high angles the geometry of the system introduces additional errors.

When the sun is on the horizon, the plane of polarization is vertical, passing through the zenith. The sky compass is most sensitive at this time. If the sun is within a few degrees of the horizon, the loss of sensibility is too slight to be noticeable. Thus, the most accurate results are obtained when the sun is too low for convenient observation by astro compass or during twilight—when it is most needed.

Theoretically, the sky compass can be used at any time of the night, but when the sun reaches a negative altitude of about 7 or 8 degrees, the amount of polarized light in the sky begins to decrease sharply and the lack of total brightness makes readings more difficult. But by this time the stars are available for use with the astro compass.

A heavy cloud layer overhead intercepts all of the polarized light, leaving none for observation. Also, the sky compass does not function when a white haze appears in the field of view, unless the sun is below the horizon and the haze is not illuminated directly. Clouds between the observer and the sun do not interfere with the sky compass, as long as the zenith is clear. However, light reflected from clouds on the opposite side of the observer from the sun do have a disturbing effect, since the light reflected from such clouds is polarized with respect to the clouds. The maximum effect occurs when the cloud fills one quadrant of the sky, centered on 135° from the sun. At such a time the reading may be several degrees in error.

The moon has a similar effect, but since the brightness of the full moon is about 1/450,000 that of the sun, the effect is of little practical significance. The maximum effect of the moon occurs when it is about 10 to 20 degrees above the horizon and about 140° from the sun (about three days before or after full moon), when the error introduced is less than 1°. The azimuth of the moon can be determined, though with a low order of accuracy, within a few days of full moon if the sun is at least 10 or 12 degrees below the horizon and the moon is not more than a degree or two below the horizon or not more than 45° above it. But normally the astro compass would be available at such a time.

Several other factors exert small disturbing effects.

The polaroid is not effective for either red or violet light and since these colors are prominent in the scattered light of the sky, the result is a loss of efficiency.

If the cellophane is not a perfect half-wave plate—of the proper thickness to produce an exact 180° phase shift of one component—the light which leaves it is *elliptically* rather than *plane* polarized, resulting in a slight reduction in contrast between bright and dark portions, with a resulting loss of sensitivity.

Absorption of light in the cellophane or loss of intensity by reflection may result in a shifting of the match points. For strongly polarized light this effect should not produce an error of more than one degree, but the effect increases as the degree of polarization becomes smaller until at low percentage of polarization there might be complete failure of the instrument.

If the light does not pass perpendicularly through the analyzer, a rotation of the plane of polarization may result. The error from this cause will rarely exceed about one degree unless the window through which the observation is made is not perpendicular to the line of sight, as when the instrument is mounted off-center in an astrodome, when the error might be large, due principally to the fact that light is partly polarized by reflection at an inclined surface.

If the instrument is not properly leveled, an error is introduced if the line of sight makes an angle with the meridian. The error is proportional to the altitude of the sun, being small for low altitudes and increasing as the altitude increases.

The ability of the eye to detect difference in brightness of the two parts of the optical element is ordinarily quite high, but varies somewhat with individuals and in the same person with different degrees of total brightness.

Near the surface of the earth the contamination of the air by smoke, dust, water vapor, etc. has a slight disturbing effect which decreases with increased height.

USING THE SKY COMPASS

Only four of the instruments have been made to date. The only extensive use made of the sky compass has been by the 375th Reconnaissance Squadron (VLR) Weather of the USAF, which has carried one of the instruments on many of its Ptarmigan flights from Fairbanks to the north pole. When, in 1949, the personnel of this Squadron received one of the sky compasses for testing, they found it necessary to adapt the mounting to fit the astrodomes of their B-29' and to determine a method of aligning the instrument with the longitudinal axis of the aircraft. By the use of some ingenuity and a little mechanical dexterity these problems were solved.

Then it was considered desirable to adapt the instrument to grid navigation, to eliminate intermediate steps. This was done by setting the clock to Greenwich apparent time and assuming a position at the north pole. Near the pole this system worked well, but as the distance between the observer and the Greenwich meridian increased, the error in the assumption became increasingly large, amounting to several degrees under some conditions over the northern coast of Alaska. This problem was solved by using a *celestial coordinator* for determining the difference in azimuth at the pole and the position of the aircraft and applying this as a correction to the observed azimuth. It took but a few seconds to find and apply the correction.

During summer months there is no twilight in polar regions. During the winter, twilight can be avoided by scheduling night missions. But near the equinoxes flights of 16 to 17 hours duration, such as the Ptarmigan, cannot entirely avoid twilight, even with careful planning.

The Pfund Sky Compass has eliminated the fear of twilight for the properly equipped polar navigator. It has proved easy to use and has given practical accuracy. The author made several polar flights during the summer of 1949. Two of these were scheduled for the most critical time—late in September and early in October. On one of these flights the aircraft was over the pole when the sun was just below the horizon, requiring a turn under the worst conditions. The entire flight was made with no loss of continuity. The shift from astro compass with the stars to sky compass to astro compass with the sun was made without incident or loss of confidence and almost as easily as shifting from observation of a star to that of the sun by astro compass, without the intermediate step.

With recent improvements in other instruments and with careful planning, the Pfund Sky Compass is not an absolute necessity, but is a valuable safety device and renders a flexibility to operations sufficient to justify further development, which is being carried out by the Air Force at Wright Field.

Thus, a principle discovered in 1669 is used in 1950 to fill an important gap in navigational instrumentation. What principles being discovered today will be used by the navigator of to-morrow ?

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