The Shipboard Use of a Low-Level Atmospheric Thermograph in Fog and Stratus Investigations

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ABSTRACT

A Low-Level Atmospheric Thermograph (LLAT) to obtain fine-scaled and detailed vertical temperature profiles to an altitude of 1000 m has been developed through a simple modification of the Sippican Expendable Bathythermograph (XBT) system. Only minutes are required for converting the system from one mode to the other, so taking atmospheric soundings does not prevent the use of the same system for oceanic soundings. Changes in temperature gradient occurring within 3 m altitude intervals are detected, thus detail previously unavailable in low-level soundings is obtained routinely. The acoustic sounder and LLAT are complementary instruments for investigating marine layer dynamics. LLAT temperature profiles allow accurate interpretation of layer backscattering detected by the acoustic sounder. The acoustic sounder allows precise height calibration for the LLAT. Because the LLAT is readily available and simple to use, temperature profiles may be obtained opportunistically at sea as various marine layer events are encountered. Profiles obtained in this manner under conditions of fog and stratus formation and persistence are presented.

1. Introduction

Measurement of air temperature as a function of height is of central importance in most experimental meteorology problems. We have developed a Low-Level Atmospheric Thermograph (LLAT) to obtain fine-scaled, detailed, vertical temperature profiles to 1000 m. The LLAT was devised by simple modification of the Sippican Expendable Bathythermograph (XBT) system. The method was developed principally for shipboard use for the Naval Postgraduate School marine fog research programs[3,4] (Norton, 1978). It is especially convenient for shipboard use since the XBT system is standard equipment on most research vessels and ships operated by the U.S. Navy and Coast Guard.

A number of other systems have been and are in use to obtain vertical profiles over the ocean and all have their own particular strengths and weaknesses. Fixed sensors on towers can be of high precision but they are limited in height to a few tens of meters. Retrievable sensors carried aloft on kites and kytoons may be used over the first few hundred meters, but height determination is difficult unless a pressure sensor is included in the instrument package. Radiosondes and rawinsondes obtain data to great heights and delineate gross features of temperature distribution, but the resulting profiles lack detail.

As will be shown, conversion from XBT to LLAT is extremely simple and the electronic recording equipment of the XBT can be used without alteration. Conversion from one system to the other requires only a few minutes if basic preparations are made in advance. Thus, taking atmospheric soundings does not prevent the same system's use for oceanic soundings immediately before or after the atmospheric sounding.

2. Equipment and methods

A schematic of the LLAT system is shown in Fig. 1. The system consists of the following: 1) the airborne unit comprised of a lifting balloon, sensor, holder and leads; 2) the shipboard launching mechanism; and 3) the readout. The probe, a streamlined plastic canister, is mounted horizontally under the balloon. This probe contains the sensor, a thermistor, and a spool of twin copper leads which connect the thermistor to the shipboard readout. The lead wire is wound on two spools, one in the probe and the other in the launcher-canister so that despooling occurs at both ends to accommodate balloon rise and ship motion.

The LLAT probe used to sound the marine boundary layer differs from the XBT probe in two

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[4] Peterson, C. H., 1975, Fog sequences on the central California Coast with examples. Naval Postgraduate School, NPS-58LR-75091.

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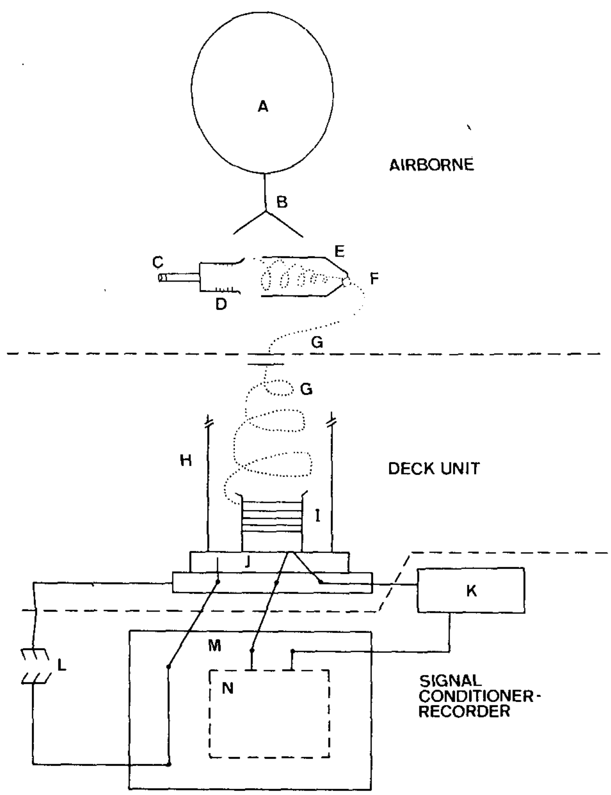

FIG. 1. Diagram of Low-Level Atmospheric Thermograph showing airborne, deck and signal conditioner-recorder units. The airborne unit is carried aloft by a balloon (A) attached by a harness (B) to the measuring probe, which consists of a thermistor (C) and lead wire spool (D). A plastic case (E) having a modified orifice (F) encloses the wire spool so that additional force is required to pull the lead wire (G) from the spool during ascent. The deck units consists of a canister (H) containing the second lead wire spool (I) which is electrically connected through the launcher-holder (J) to the signal conditioner-recorder and ground (L). The conditioner-recorder consists of a pre-recorder signal conditioner (K) and the recorder unit (M) which contains the measurement bridge, amplifier and recorder (N).

ways. First, the 516 g lead nose piece was removed, making the probe light enough to be carried aloft by the standard 100 g pilot balloon. Second, the probe case orifice through which the lead passes was restricted so that approximately twice the force was required to pull the wire from the probe as from the deck canister. It was necessary to restrict the orifice because the wire lead can fall from the probe under its own weight and wind drag as the balloon ascends. As an additional precaution, the probe was suspended in a harness which holds the wire spool horizontal. The restricted orifice and horizontal mounting reduced free despooling, giving uniform ascent. Forces of 300 and 600 dyn were needed to despool at the canister and probe ends, respectively, which created negligible drag on the balloon ascent. Best results were obtained if less than 30 m of lead wire fell on the sea surface. If there was much more wire in the water, despooling proceeded mostly from the probe end, resulting in rapidly accelerating ascents and reduced altitude. The two-to-one force ratio and the weight of the wire which pulls on the probe acted to produce uniform despooling at both ends of the system.

Since it was undesirable to have the balloon trail a long length of lead as it moves aloft once the sounding is completed, we insured that the lead dropped from the probe in the following manner. The twin lead was cut between the thermistor and spool in the probe and the individual wires were rejoined with a single small half loop on each end. The ends were held together with a small drop of silver paint, which had no mechanical strength but made good electrical contact. The weight of the trailing lead when despooling was completed caused the wire to part at this junction, dropping the lead into the sea.

The 100 g pilot balloons were filled to produce ascent rates between 3 and 4 m s^{-1}. The rate varied somewhat with altitude, being slightly more rapid at higher elevations due to reduction of pay load weight

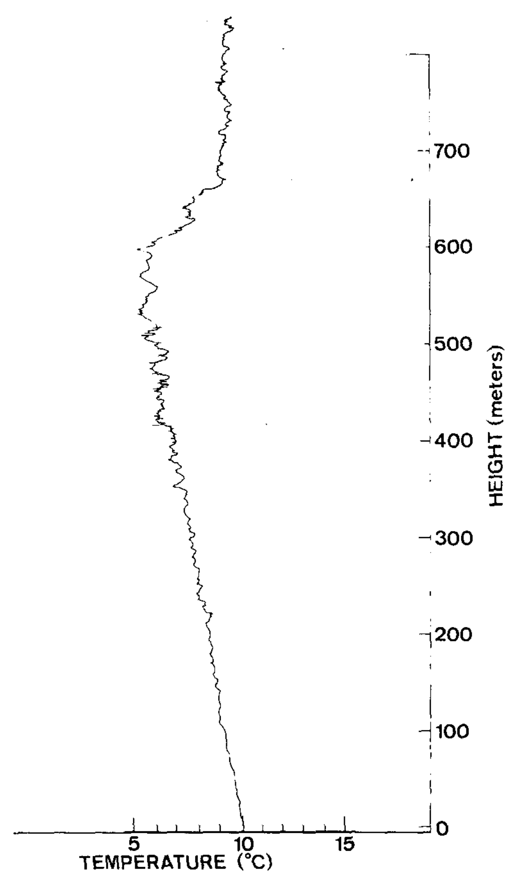

FIG. 2. Vertical profile of temperature showing variation in fine-structure from the sea surface through a high stratus layer (top between 600 and 700 m). The abstract of this facsimile record is shown in Fig. 4c.

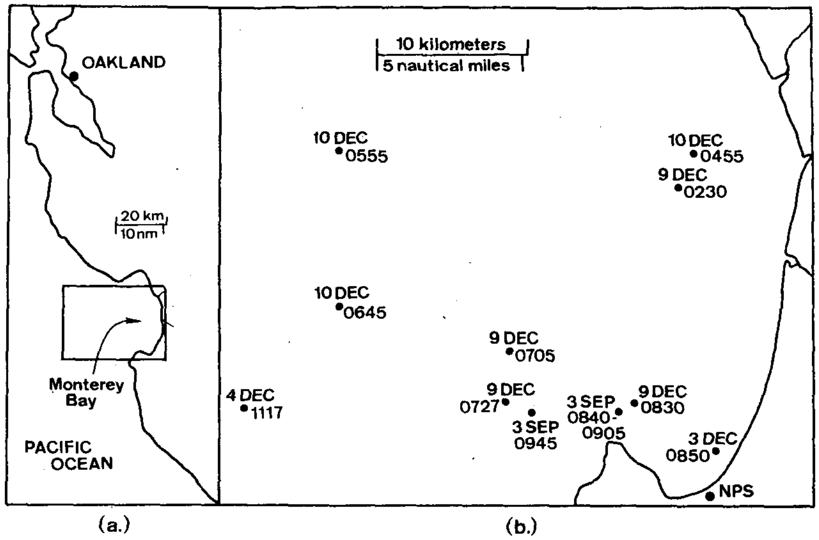

FIG. 3. The location of Monterey Bay on the central California Coast (a). The area boxed in Fig. 3a is enlarged in Fig. 3b and shows the locations of LLAT soundings and the Naval Postgraduate School (NPS) in Monterey on southern Monterey Bay. The location of the Oakland soundings on the eastern shore of San Francisco Bay is shown in Fig. 3a.

as lead is despooled. This was especially true at higher wind speeds (where lead breakage is also more likely). Balloon height was determined from elapsed time and ascent rate. The rate was determined as a function of pilot balloon free lift, probe weight and time, using the techniques of the Meteorological Office (1961) adjusted to conform to the ascent tables for 100 g pilot balloons of the U.S. Weather Bureau.[5] This method was most accurate when the surface wind speed was less than 5 m s^{-1}. At greater wind speeds, ascent was increased due to increased despooling from the probe as the balloon moved horizontally. Height calculations under high wind conditions are complex.

Expendable bathythermograph probe thermistors have an accuracy better than ±0.1°C and a time constant $t < 0.2$ s in water (Demed, 1969). For the system including recorder, $t = 1.0 \pm 0.2$ s in water. In air, $t = 1.6 \pm 0.2$ s for the system. This relatively fast response allows continuous, detailed profiles to be obtained. Changes in temperature on vertical scales < 3 m are readily detectable, as shown in Fig. 2.

An XBT readout contains a thermistor bridge, trigger logic, power supply, signal connection circuitry and strip chart recorder. When the system is used in the XBT configuration control circuitry starts the chart drive when the probe enters the water and the drive stops automatically when the chart has moved through the one depth cycle. For use as an LLAT, both the start and stop circuits must be deactivated and the chart set in continuous motion and stopped through operation of the recycle switch. To accomplish deactivation one grounds the signal connection circuitry at the input terminal board and bypasses the microswitch which stops the recorder. Adding a switch to the bypass on the trigger logic circuit board makes alternate use as an XBT and LLAT possible.

Since the ground return of the XBT system was changed by modification to LLAT the temperature calibration was also changed. It was necessary to perform a temperature calibration of each sensor before launch. Two calibration methods were used: 1) the sensor was immersed in two water baths at different temperatures and the readings on the output stripchart noted; 2) the sensor was calibrated by comparing it with another instrument in use such as a radiosonde, using the extremes of measured temperature. This latter method was less desirable since it was difficult to insure that two different points on a ship were at the same temperature if the sensors were not very close together.

It is possible to change the temperature span of the system output by changing the total resistance of the signal conditioning package. For the work reported here, a set resistance was used to modify the span so that the range changed slightly from sensor to sensor due to variation in sensor resistance. By using a variable resistance it would be possible to adjust system response so that a 1°C temperature change always spans a convenient chart interval.

A problem with the LLAT system arose from inaccuracies in height determination due to varying

[5] NAVAER, 1973: Tables for computing horizontal distance of pilot balloons (100 gms). Chief of Naval Operations, NAVAER 50-1B-501.

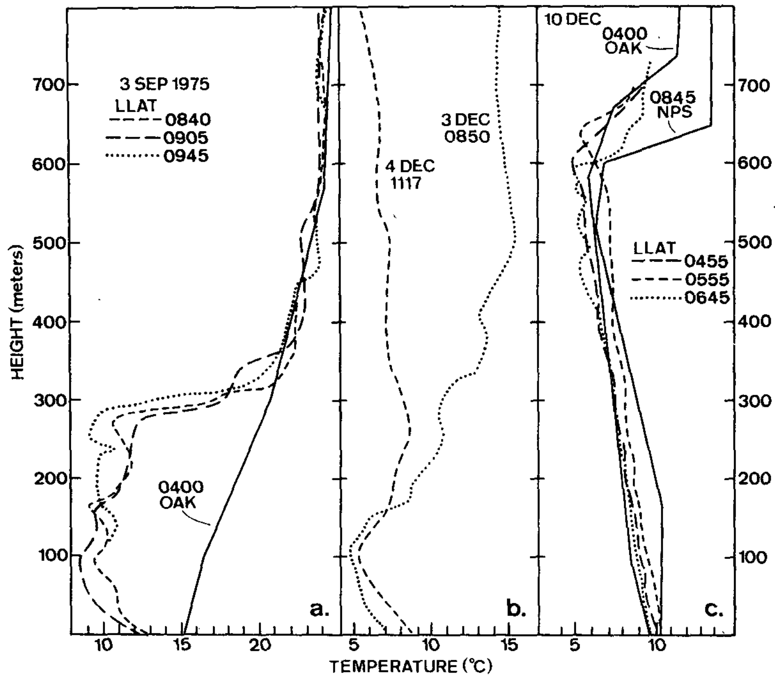

FIG. 4. Soundings obtained under various conditions. (a) The time series obtained by LLAT is compared to a standard radiosonde obtained at Oakland. Soundings similar below 200 m but widely different above are shown in (b). In (c) LLAT profiles obtained at sea are found to be quite similar to radiosondes obtained at shore stations in Oakland and Monterey.

wind drag and balloon buoyancy. This problem was eliminated by an independent height calibration. Many of the Naval Postgraduate School cruises utilize an acoustic sounder to monitor the marine inversion. The sounder identifies the base of the inversion to within ±20 m allowing an accurate height calibration to be made. In Section 3 comparisons of acoustic sounder and LLAT determined inversion heights are shown.

It is useful to compare the LLAT with the standard radiosonde which is in widespread use (Middleton and Spilhaus, 1953). The standard radiosonde (RAOB) has several advantages: both temperature and humidity profiles are obtained, height is measured directly, and great heights can be reached. The LLAT on the other hand gives a continuous, real-time, very precise temperature profile of the lower levels of the atmosphere. The two systems actually complement each other and use of one does not preclude use of the other. If the main interest is a detailed investigation of the marine boundary layer, then the LLAT will be of most use, whereas the RAOB will be needed to probe the atmosphere above the marine inversion. Naval Postgraduate School cruises have shown that the ideal data acquisition method is to use twice a day RAOB's, continuous monitoring of the inversion height with an acoustic sounder and frequent LLAT releases.

The Sippican XBT system has been found ideal for routine use at sea. It is readily available, dependable and requires little maintenance with proper use. However, for special purposes including thermal turbulence studies, better accuracy and heightened sensitivity might be obtained by decreasing balloon buoyancy in low wind conditions, filtering noise pickup by the long leads, increasing data recording speed, and replacing the supplied thermistors with thermistors which have shorter time constants.

3. Results

The lower section of an LLAT taken on 10 December 1975 at 0555 local standard time (LST) is reproduced in Fig. 2. The relatively rapid system response and continuous profile allow temperature fluctuations to be recorded on a variety of scales from 3 to 30 m. The profile in Fig. 2 shows increasing structure from the surface to 550 m, followed by large fluctuations in the region of the inversion between 600 and 700 m. Above the inversion fluctuations decrease, indicating that the observed temperature inhomogeneities are not due to electrical noise, even in this unfiltered signal. Additional soundings taken on this date at 0455 and 0645 LST show similar turbulence patterns. Fig. 2 clearly illustrates the possibility of using the LLAT in the study of turbulence to heights of 1000 m.

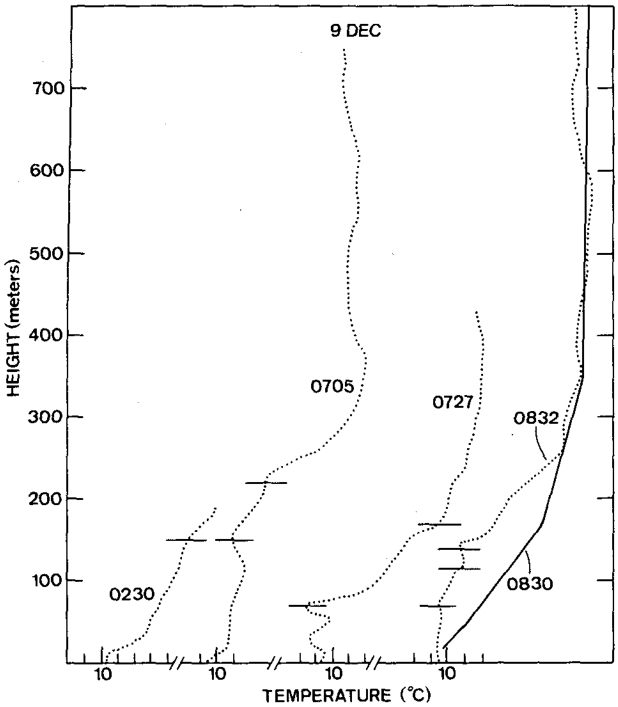

FIG. 5. LLAT profiles obtained before (0230), during (0707, 0832) and after fog formation on Monterey Bay and the standard radiosonde from the adjacent shore station at the Naval Postgraduate School in Monterey (0830). All times are local standard times (LST).

Data were chosen for presentation which demonstrate the LLAT's utility in probing differing atmospheric conditions and in monitoring temporal changes. Fig. 3 shows the locations of the soundings at sea on Monterey Bay, California. Figs. 4 and 5 show LLAT plots which were obtained from the original strip charts by averaging through short-term (small-scale) fluctuations so changes on a scale < 10 m are ignored.

In Fig. 4 profiles obtained under conditions of low thin stratus with patches of dense fog below (Fig. 4a), dense surface fog with clear skies above (Fig. 4b) and high uniform stratus (Fig. 4c) are compared. In Fig. 4a, the LLAT traces are compared to a standard radiosonde taken ~5 h earlier in Oakland, 120 km away (see Fig. 3). There is good agreement in temperature above the sharp 12°C inversion at 300 m among the four profiles. However, below this level the marine layer is seen to be 5–8°C cooler. Although the traces are similar below 300 m, 2–3°C variability at any given level is common. Local mesoscale fog events under clear skies occurring on consecutive December days in 1975 are shown to be quite similar below 150 m in Fig. 4b. These profiles are strikingly different from the ones shown in Fig. 4c, which were obtained under conditions of uniform overcast and good surface visibility (>10 km). The 0555 LST profile in Fig. 4c is the abstracted version of the raw data facsimile shown in Fig. 2. Fig. 4c also shows two standard radiosondes taken at Oakland and Monterey. In this case all profiles are similar.

Fig. 5 presents a time series of four LLAT profiles obtained at the mouth of Monterey Bay on the morning of 9 December 1975. At 0230 LST the sky was clear and surface visibility was more than 10 km. The profiles at 0705, 0727 and 0832 were obtained in a fog bank thick enough to obscure the sky and give horizontal visibilities less than 300 m. In Fig. 5 the height of the base of the temperature inversion as determined from shipboard acoustic sounder is indicated by a horizontal line crossing the LLAT trace. The figure shows good agreement between the LLAT and the acoustic sounder. Note that both instruments readily detect multiple inversions. The sounder missed the lowest inversion (~30 m) shown in the 0727 profile due to blanking of the sounder receiver for a short period following the transmitted pulse. The value of the LLAT in giving detailed profiles beginning at deck level is clearly evident.

The usefulness of the acoustic sounder in enabling accurate height calibration was demonstrated on 10 December when an inexperienced technician inflated and adjusted balloon lift. Height determinations were found to be considerably in error, but it was possible to adjust the LLAT height scale, since inversion height was determined by the sounder. The acoustic sounder is especially useful in height calibration in high wind conditions, where LLAT height determination becomes more difficult.

4. Discussion

Figs. 4 and 5 include profiles obtained from RAOB observations at Oakland and Monterey (NPS). We do not expect to obtain the same soundings in Monterey Bay and Oakland, but where relatively stable conditions do exist, as on 10 December (Fig. 4c), the main features appear widespread and are conspicuous in all soundings. This result is in good agreement with the findings of Neiburger (1944, 1960). However, where thermal relationships are changing rapidly, 5°C differences between LLAT soundings obtained at sea and RAOB's obtained at land-based stations are not uncommon as shown on 3 September (Fig. 4a) and on 9 December (Fig. 5). These data illustrate the use of the LLAT in measuring thermal profiles at the site of observation rather than having to depend on shore based observations which may be quite removed in space from the mesoscale conditions important at the observation site.

Note the similarities among the profiles obtained on 3 September 0840 and 0905 (Fig. 4a), 3 and 4

December (Figure 4b) and 9 December at 0832 (Fig. 5). These profiles are similar below an inversion with base at ~100 m. In each case the surface horizontal visibility was less than 300 m. Although similar in this layer next to the sea surface, the upper profiles are found to be quite dissimilar, ranging from an extreme inversion on 3 September to an almost isothermal layer above on 4 December. The similarities of these profiles could easily be overlooked in standard radiosonde procedure. Finding this agreement between surface visibility observations and low-level vertical profiles is suggestive of possible causal relationships and worthy of additional study.

A review of the time series obtained on 9 December 1975 (Fig. 5) suggests that the lower level thermal profiles over the sea are dynamic and determined by the particular processes occurring therein. On 9 December the process occurring in the first 200 m above the sea surface was fog formation. As the fog developed a surface inversion was elevated to an altitude of 140 m. The first sounding of the series was taken at 0230 under clear skies with more than 10 km surface visibility. This sounding showed a strong surface inversion of about 3°C in the first 50 m, with a continuing increase up to 350 m where the air was 9°C warmer. No fog was observed until 0630 when what appeared to be a local area of fog formation was observed ~3 km southwest of the ship. The fog bank appeared to taper to a thickness of a few tens of meters on its eastern edge. The ship entered this surface cloud from the northeast and took the 0705 sounding near its thin eastern edge. The fog was probably confined to within the sharp surface inversion shown in this sounding. The sounding at 0727 shows a layered structure and general cooling up to 60 m. At 0832 when the last sounding was taken the cooled layer extended to 140 m and intermediate stratification had become less obvious. At the same time a RAOB was obtained overland at the Naval Postgraduate School in Monterey. The two soundings were only 7 km apart, but the one over land was in sunny clear air. The RAOB shows no detail below 170 m and the air overland at this height was 5°C warmer than that in fog at sea. At 250 m and above there was no temperature difference.

5. Conclusions

The Sippican XBT system has been successfully modified to make precise temperature soundings of the first 1000 m above the ocean surface. In routine use, continuous profiles are obtained showing temperature variations as small as 0.3°C and inhomogeneity sizes as small as 3 m.

LLAT profiles have been obtained in various situations associated with west coast fog and stratus systems. Comparison of the observations of fog forming activity and visibility at the points of LLAT soundings at sea and points of routine radiosonde observation on land show wide disparity in lower level profiles and visibility observations. The desirability of obtaining profiles at the point of observation at sea is clearly indicated. Preliminary results suggest that fog formation and other lower level marine layer processes are important in determining thermal profiles found in these layers at the observation site. The ready availability, dependability and ease of operation of the LLAT will make it an effective tool for investigating such phenomena on a routine or opportunistic basis and establishing causal relationships.

The LLAT, acoustic sounder and radiosonde are complementary in assembling detailed studies of low-level atmospheric phenomena in the marine layer. The LLAT is used to obtain vertically continuous temperature profiles, the acoustic sounder gives temporally continuous records of discontinuities in temperature gradient from 30 to 1000 m, and the radiosonde is used to verify gross features shown by acoustic sounder and LLAT and to link them to synoptic analysis through upper level profiles. When conditions such as high winds bring LLAT height determination into doubt, the acoustic sounder is especially useful in adjusting or verifying the LLAT altitude scale.

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