A Gated, Wideband Magnetic Direction Finder for Lightning Return Strokes

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ABSTRACT

A magnetic direction finder has been developed which utilizes only the initial few microseconds of wideband return stroke waveforms to provide accurate directions to the channel bases of lightning discharges to ground. Bearing errors are minimized because, near the ground, most channels tend to be straight and vertical with no large branches or horizontal sections. Tests on a number of lightning storms at distances of 10 to 100 km indicate the angular resolution is in the range from 1° to 2°, with little or no systematic dependence on azimuth or distance.

1. Introduction

For lightning research and other applications, it is often necessary to determine accurate locations of lightning discharges to ground. One technique which has been in use since the 1920's employs the magnetic cathode-ray direction finder (CRDF), originally described by Watson-Watt and Herd (1926). The historical development of CRDF's and their overall accuracy have been reviewed by Ockenden (1947), Adcock and Clarke (1947), Norinder (1953), and Horner (1954, 1957). In a typical installation, a pair of orthogonal loop antennas tuned to a VLF frequency, typically 10 kHz, detect the horizontal magnetic field produced by lightning. The azimuth angle to the discharge is obtained by displaying both antenna outputs simultaneously on an *x-y* oscilloscope, so that the resulting vector points in the direction of the discharge. Two or more CRDF's at known positions are sufficient to determine the location of a discharge from the intersection of simultaneous azimuth vectors.

Unfortunately, the accuracy of conventional VLF direction finders is poor at distances $\lesssim$200 km because the antennas sense not only the magnetic field from the vertical lightning channel but also the field produced by horizontal channel sections of large extent and by ionospheric reflections; furthermore, these fields may be altered by the effects of terrain on propagation (Horner, 1954, 1957). These so-called polarization errors produce elliptical patterns on the oscilloscope, rather than the ideal straight vectors, with the result that the azimuth angles to the discharges are poorly defined. In a recent study in Japan, Nishino *et al.* (1973) found ellipticities approaching 0.5 at distances of about 200 km, which correspond to bearing errors in excess of 20°. The distortions produced by ionospheric reflections can be minimized by displaying only the initial ground wave portion of the VLF signals (Adcock and Clarke, 1947), but, as a practical matter, bearing errors of $\pm 10°$ are common within 100 km (Kidder, 1973).

Recent broadband measurements of the magnetic fields produced by lightning within 200 km and as close as 1 km show that most return stroke waveforms in discharges to ground have zero-to-peak rise times in the range from 1 to 5 μs (Krider and Noggle, 1975; Uman *et al.*, 1975b). Since the propagation speed of a return stroke up a previous leader channel is between 10^7 and 2×10^8 m s^{-1} (Schonland, 1956), these initial peak fields must originate within a few tens to a few hundreds of meters above ground level, a region in which the channel is usually close to vertical. A general description of the production of magnetic fields by return strokes has been published by Uman and McLain (1969) and Uman *et al.* (1975a). Since the initial magnetic field changes are fast, the peaks are almost entirely due to the radiation field term in the general field equations, even within 10 km (Uman *et al.*, 1975b).

Here, we present a new version of the cathode-ray direction finder, which utilizes only the initial portion or peak of magnetic waveforms to provide accurate directions to the channel bases of individual return strokes in discharges to ground. A detailed analysis of the accuracy of the technique as a function of time in the magnetic waveform is presented in a companion paper by Herrman *et al.* (1976). The direction finder operates effectively for discharges as close as a few kilometers and, in principle, as far away as those de-

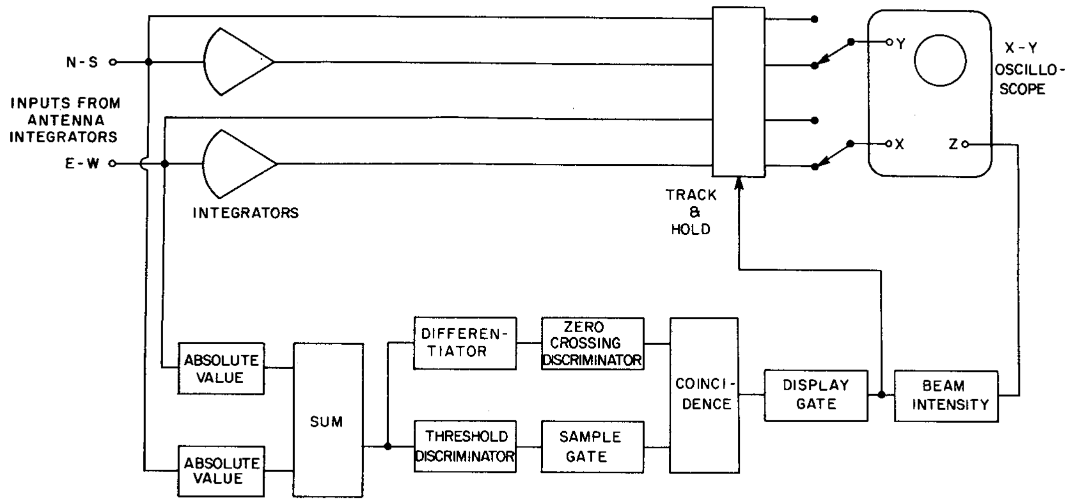

FIG. 1. Block schematic diagram of the gated magnetic direction finder electronics.

tected accurately by conventional direction finders. As we shall see, the signals from most intracloud discharges can be rejected by a suitable choice of trigger thresholds and gate requirements.

2. Apparatus

Two vertical and orthogonal wideband magnetic field antenna systems, similar to those described previously by Krider and Noggle (1975), are the basic detector elements. The output of each antenna system is proportional to the lightning magnetic field multiplied by the cosine of the angle between the plane of the antenna and the discharge. Fig. 1 shows a block schematic diagram of the gated direction finder, and a detailed schematic is given in Fig. 2. The magnetic field signal from each antenna system goes either directly or through an integrator to a track-and-hold circuit, which is switched to hold when a display gate is generated. The resulting voltage levels, which are proportional to the incident field or to the integral of the field up to the time the gate is generated, then decay exponentially with equal time constants while the display gate is on. These two signals are displayed simultaneously on an *x-y* oscilloscope for the duration of the display gate and provide a vector segment which points in the direction

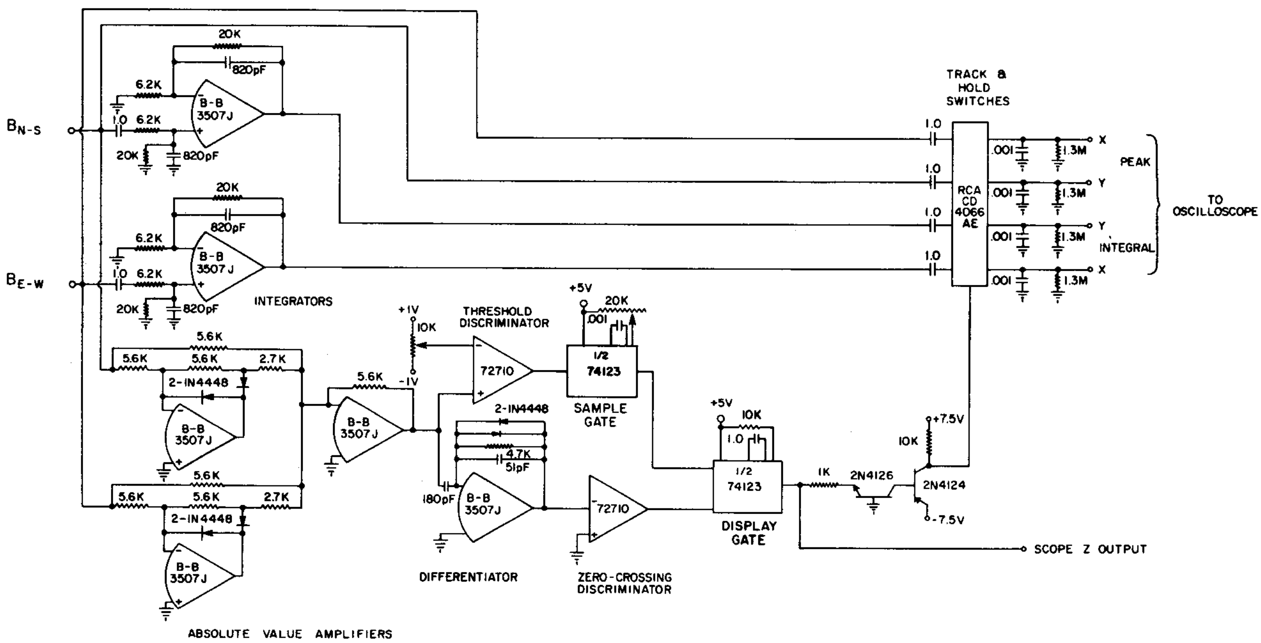

FIG. 2. A detailed schematic diagram of the gated magnetic direction finder electronics.

of the lightning source. Operation in the integrate-to-peak mode offers better rejection of any high-frequency background noise when ranging on distant (over 200 km) storms.

The display gate can be generated a fixed time interval after the initial field is detected; or it can be generated at the time the magnetic field goes through a peak value. The latter method, which is shown in Figs. 1 and 2, has the advantage that many intracloud discharge signals can be rejected by requiring the peak of the incident field to occur within a preset time interval, typically 0 to 8 μs, after the start of the field. If the peak does not occur during this interval, the waveform is ignored. Since only the initial portion of a waveform is used, relatively large filters can be employed in the antenna circuits to reject ambient 60 Hz noise, if necessary. Of course, carefully matched components must be used to keep the gains of both antenna systems, the integrators, and the track-and-hold circuits identical to within a fraction of a percent.

In Figs. 1 and 2 each magnetic field signal goes to an absolute value amplifier, and the sum of the absolute values triggers the sample gate whenever the incident field is above a preset level. The summed signal is also differentiated, and if this derivative goes through zero during the time the sample gate is open, a zero-crossing discriminator triggers the display gate. The display gate opens the track-and-hold switches, which are normally closed, and also turns on the x-y oscilloscope beam for the duration of the gate. A track-and-hold decay-time constant of 1.3 ms provides a vector which is easily viewed on a low-frequency oscilloscope, and a display gate duration of 2 ms has been found to be satisfactory for most applications.

On the oscilloscope, the distance from the tip of the vector segment to the origin is proportional to the peak, or integral to the peak, of the incident magnetic field intensity and can be so calibrated. If the tip of the vector goes off-scale, the peak field value can be determined from the point where the vector turns off when the display gate terminates. The display gate width is constant, and since the vector decays exponentially in time, the turn-off point will be at a constant fraction of the peak field. Since the polarity of the initial magnetic field signal is preserved, there is no 180° ambiguity in the azimuth display for the vast majority of return strokes which transfer negative charge to ground (Uman, 1969).

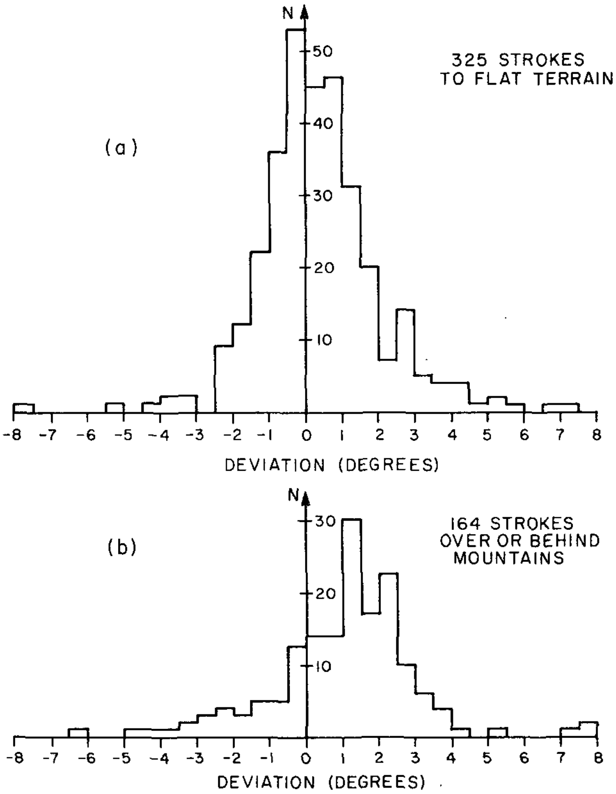

FIG. 3. Histograms showing the differences between actual and magnetic azimuth angles for (a) 325 return strokes striking level terrain and (b) 164 return strokes striking mountains.

3. Test results

Gated wideband CRDF's similar to that described above were operated at single stations in both Arizona and Florida, in order to determine the general feasibility and angular resolution of the system. These initial tests clearly showed that the wideband gating technique works well in both locations. Large magnetic vectors, which were assumed to be return strokes, pointed in the directions of isolated storms, as determined by weather radars, and vectors corresponding to separate return strokes in discharges to ground were parallel to within 1°. On some storms, the large return-stroke vectors were accompanied by additional small vectors with a more random, generally backward orientation and often delayed a few milliseconds from the return strokes. These were probably due to intracloud discharge processes such as K-changes (Ogawa and Brook, 1964); but usually a trigger threshold could be found which, for isolated convective storms, accepted more than 90% of the return strokes to ground and rejected almost all the intracloud discharges.

In order to determine the angular resolution of the technique more precisely, a single-station CRDF was operated in Arizona, in correlation with a television camera which recorded the location and geometry of visible lightning channels near the ground. A second TV camera viewed the CRDF oscilloscope. Both cameras were driven by a common sync-generator so that the video signals could be mixed and recorded on the same video tape recorder. The lightning camera had a horizontal field of view of 16°, and the azimuth angle to the point where a visible discharge contacted ground could usually be measured to an accuracy of about 0.2°. The angles of return-stroke vectors, which were superimposed on the lightning images, could be determined to an accuracy of about 1°.

For these resolution tests, the magnetic field peaks were detected (rather than the integral-to-peak), and the sample gate width was kept at 5 μs. Single-turn coaxial cable antennas (Krider and Noggle, 1975) with an area of 1 m^2 were used, and the antenna integrator decay-time constant was about 40 μs. The antenna loops were arranged in a delta pattern, with the tops held by a common support mast and the lower vertices held by a carefully machined orthogonal frame.

Fig. 3a shows a histogram of the differences between the actual and the magnetic bearings as recorded by the two TV cameras for 325 separate return strokes striking flat terrain. The full width at half maximum (FWHM) of the distribution of bearing errors in Fig. 3a is about 2.5°, and the standard deviation is about 1.8°. Fig. 3b shows a histogram of the differences between the TV and CRDF bearings for 164 return strokes which were recorded in or behind mountainous terrain. For these discharges, the mean deviation was about 1°, the full width at half maximum about 3.5°, and the standard deviation about 2°.

The means and standard deviations of the individual storms which are combined in Fig. 3 and which produced 10 or more strokes to flat terrain are shown in Fig. 4 as a function of average azimuth angle. The means of the bearing errors in Fig. 4 are within 1° of zero for most storms, and there appear to be no systematic shifts in the means at different azimuth angles.

The azimuth angle differences which are shown in Figs. 3 and 4 represent the superposition of measurement errors, typically about 1°, the effects of non-level terrain or tortuous channel geometry, and the scattering of the magnetic field between the return-stroke channels and the antenna. Apparently, the effect of tilted or non-level terrain is to produce the systematic shift in the mean for the mountain storms in Fig. 3b, but the resolution is still adequate for most applications. When the discharges were behind small hills, the errors in bearing angles were similar to those over flat terrain.

The distances to the discharges plotted in Figs. 3 and 4 were not accurately measured; but all were within 100 km, and several were within 10 km. A plot of the bearing errors for individual strokes as a function of angular stroke height estimated from the TV records (to give an approximate range) indicates no dependence of angular resolution on distance. It is interesting to note that the CRDF system which recorded the data plotted in Figs. 3 and 4 was installed on the roof of a building about 35 m in height on the campus of The University of Arizona, near other antennas and in the middle of the City of Tucson, which indicates that the system is relatively immune to site errors.

4. Discussion

As mentioned above, electronic gating techniques have previously been used to improve the accuracy of

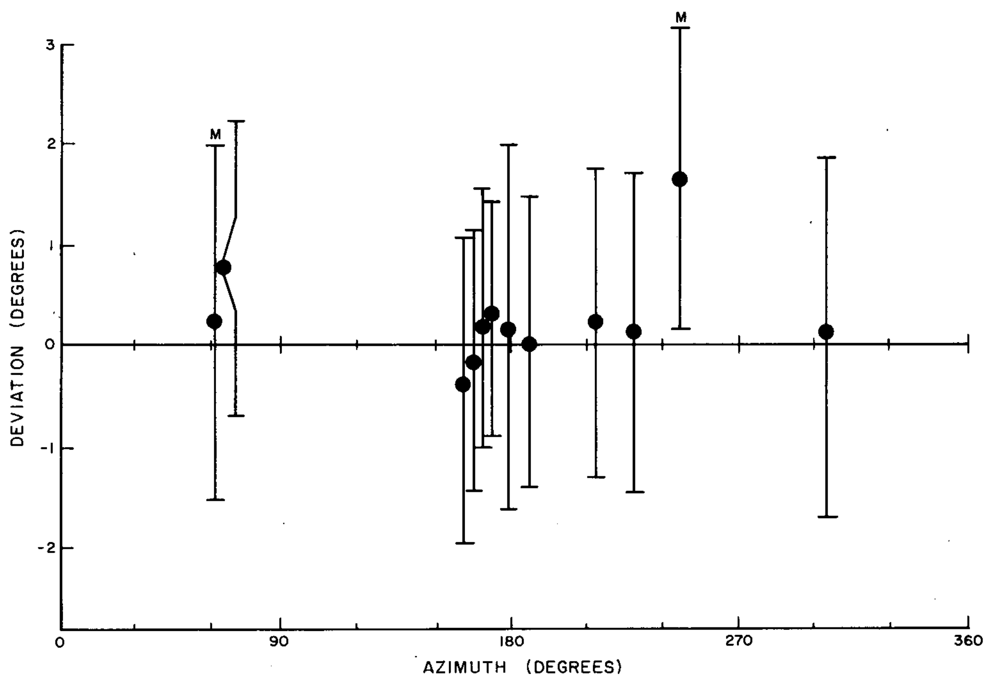

FIG. 4. The means (dots) and standard deviations (bars) of bearing errors for individual storms as a function of average azimuth angle. Those storms over mountainous terrain are indicated by M.

VLF magnetic direction finders (Adcock and Clarke, 1947). In a typical case, only the first 100 μs of the antenna outputs are displayed on the oscilloscope, to reduce polarization errors and also to remove any 180° ambiguity in the bearing. A similar technique was employed by Taylor and Jean (1959), Taylor (1963) and Larsen and Stansbury (1974) who used antennas with an upper-frequency response of 100 to 200 kHz. To the best of our knowledge, the efforts reported here represent the first attempt to gate a wideband direction finder in order to restrict observation of the magnetic waveforms to just those times when the return-stroke currents are close to the ground.

As we have seen, a gated wideband CRDF provides an azimuth angle resolution for the channel bases of individual return strokes in discharges to ground in the neighborhood of 1° to 2°, a value which is significantly better than that of previous magnetic systems on close lightning. The reason for this improved accuracy is that near the ground most lightning channels tend to be straight and vertical, and the polarization errors due to large branches and horizontal channel sections are minimal. Other direction-finding techniques, such as multi-station time-of-arrival methods in the VLF frequency range (Lewis *et al.*, 1960) and the VHF (Oetzel and Pierce, 1969; Proctor, 1971; Cianos *et al.*, 1972), are also insensitive to polarization errors and can, with some difficulty, achieve good angular resolution on close lightning. Since the VHF arrival-time method is sensitive to all sources of VHF radio noise, intracloud discharges are located as well as individual return strokes in discharges to ground.

The main advantages of the gated magnetic technique are as follows:

1) The system can be made relatively insensitive to intracloud discharges, which is often desired when attempting to detect lightning-caused forest fires or when locating possible interruptions of electric power distribution systems. In our tests, most intracloud discharges could be rejected by a proper choice of trigger level and sample gate width. The few intracloud signals which were displayed were usually recognizable by their small amplitude relative to return strokes and their typically random orientation. In an automatic system, improved intracloud discharge rejection could be obtained by adding logic gates to insure that the incident magnetic field also has a fall time and total duration characteristic of a return stroke.

2) The magnetic antenna systems and direction-finding electronics are simple, reliable, and easy to construct using modern solid-state components.

3) The signal outputs are voltage levels which are available in real time and which are easily interfaced to a microprocessor or an automatic data acquisition system.

4) Since the first few microseconds of a wideband magnetic waveform are almost entirely due to the radiation field term in the general field equation (Uman *et al.*, 1975a, b) and since the radiation field is proportional to the reciprocal of the distance to the discharge, measurements of the peak field intensity by two or more separated stations might also be used to locate the discharges. This method, which is based on the intersection of two or more circles, is independent of the azimuth-angle method and could possibly provide a valuable consistency check on the locations of ground discharges in a multi-station system.

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REFERENCES

Adcock, F., and C. Clarke, 1947: The location of thunderstorms by radio direction-finding. *J. Inst. Elec. Engrs.*, **94B**, 118–125.
Cianos, N., E. N. Oetzel and E. T. Pierce, 1972: A technique for accurately locating lightning at close ranges. *J. Appl. Meteor.*, **11**, 1120–1127.
Herrman, B. D., M. A. Uman, R. D. Brantley and E. P. Krider, 1976: Tests of the principle of operation of a wideband magnetic direction finder for lightning return strokes. *J. Appl. Meteor.*, **15**, (in press).
Horner, F., 1954: The accuracy of the location of sources of atmospherics by radio direction-finding. *Proc. Inst. Elec. Engrs.*, Part III, **101**, 383–390.
——, 1957: Very-low-frequency propagation and direction finding. *Proc. Inst. Elec. Engrs.*, **104B**, 73–80.
Kidder, R. E., 1973: The location of lightning flashes at ranges less than 100 km. *J. Atmos. Terr. Phys.*, **35**, 283–290.
Krider, E. P., and R. C. Noggle, 1975: Broadband antenna systems for lightning magnetic fields. *J. Appl. Meteor.*, **14**, 252–256.
Larsen, H. R., and E. J. Stansbury, 1974: Association of lightning flashes with precipitation cores extending to height 7 km. *J. Atmos. Terr. Phys.*, **36**, 1547–1553.
Lewis, E. A., R. B. Harvey and J. E. Rasmussen, 1960: Hyperbolic direction finding with sferics of transatlantic origin. *J. Geophys. Res.*, **65**, 1879–1905.
Nishino, M., A. Iwai and M. Kashiwagi, 1973: Location of the sources of atmospherics in and around Japan. *Proc. Res. Inst. Atmos., Nagoya Univ.* **20**, 9–18.
Norinder, H., 1953: Long-distance location of thunderstorms. *Thunderstorm Electricity*, The University of Chicago Press, 276–327.
Ockenden, C. V., 1947: Sferics. *Meteor. Mag.*, **76**, 78–86.
Oetzel, E. N., and E. T. Pierce, 1969: VHF technique for locating lightning. *Radio Sci.*, **4**, 199–201.
Ogawa, T., and M. Brook, 1964: The mechanism of the intracloud lightning discharge. *J. Geophys. Res.*, **69**, 5141–5150.
Proctor, D. E., 1971: A hyperbolic system for obtaining VHF radio pictures of lightning. *J. Geophys. Res.*, **76**, 1478–1489.
Schonland, B. F. J., 1956: The lightning discharge. *Handbuch der Physik*, Vol. 22, Springer-Verlag, 576–628.

Taylor, W. L., 1963: Radiation field characteristics of lightning discharges in the band 1 kc/s to 100 kc/s. *J. Res. Natl. Bur. Stand.*, **67D**, 539–550.

——, and A. G. Jean, 1959: Very-low-frequency radiation spectra of lightning discharges. *J. Res. Natl. Bur. Stand.*, **63D**, 199–204.

Uman, M. A., 1969: *Lightning*. McGraw-Hill, 264 pp.

——, and D. K. McLain, 1969: Magnetic field of the lightning return stroke. *J. Geophys. Res.*, **74**, 6899–6910.

——, —— and E. P. Krider, 1975a: The electromagnetic radiation from a finite antenna. *Amer. J. Phys.*, **43**, 33–38.

——, R. D. Brantley, Y. T. Lin, J. A. Tiller, E. P. Krider and D. K. McLain, 1975b: Correlated electric and magnetic fields from lightning return strokes. *J. Geophys. Res.*, **80**, 373–376.

Watson-Watt, R. A., and J. F. Herd, 1926: An instantaneous direct-reading radio goniometer. *J. Inst. Elec. Engrs.*, **64**, 611–622.