TRUE GLOBAL MAPPING OF LIGHTNING USING WIDELY SPACED VLF RECEIVERS ON THE GROUND

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ABSTRACT

A network of six VLF receivers stretching from Australasia to Japan has been in operation since November, 2001. Lightning strokes can be located in real time at up to 10,000 km from this network which is being extended to cover the whole world with a projected location accuracy of 1-2 kilometres. At each receiver site, some tens of lightning impulses ("sferics") are received each second. Earth-ionosphere propagation disperses the impulses into wave trains, the first millisecond of which is processed to determine the time of group arrival (TOGA). The TOGAs are transmitted to a central station for determining the stroke location.

INTRODUCTION

True global mapping of lightning using widely spaced (a few megametres) receivers on the ground requires the use of frequencies below about 30 kHz for which low attenuation propagation in the Earth-ionosphere waveguide is possible over global distances. Time of arrival and/or magnetic direction finding at all the stations which receive the impulse ("sferic") from the same lightning stroke can be used. In the network described here, only timing is used for location and only part of the VLF band (defined as 3-30 kHz) is used. The problem of determining which sferics received on the network are due to the same lightning stroke is discussed here in detail.

TIME OF GROUP ARRIVAL (TOGA)

Short range detection of lightning strokes, at a range of a few hundred kilometres or less, uses only the first few microseconds of the received RF (radio frequency) signal, avoiding propagation via the ionosphere. Limiting the data to the first few microseconds means that only frequency components well above the VLF band are included. Such an impulse is not dispersed so its time of arrival can be determined to well within one microsecond. In contrast, long range detection requires use of Earth-ionosphere waveguide propagation in the VLF band. The wave period at such low frequencies is of the order of tens of microseconds so no sharp edge appears for precise arrival timing. In addition, the waveguide dispersion produces precursor ripples rising relatively slowly from the noise floor, thus making the "time of arrival" even more uncertain. However, the apparently lost timing information is in the sferic wave train, mainly in the first millisecond, as explained below.

The electric field, E, of a sferic at range, r, time, t, and frequency, ω, can be expressed as,

$$E(r,t,\omega) = \sum A(\omega)\cos(\phi(\omega)) \tag{1}$$

where, at any one Fourier component of frequency ω,

$$\phi(\omega) = \omega t - k(\omega)r + \phi_0 \tag{2}$$

and the wave vector, k, is dependent on frequency while the phase, ϕ_0, is not. Differentiating with respect to frequency at any time, t, and range, r, we find,

$$\frac{d\phi}{d\omega} = t - r\frac{dk}{d\omega} = t - \frac{r}{v_g(\omega)} \tag{3}$$

where $v_g(\omega)$ is the frequency-dependent group velocity.

From the definition of group velocity, the time, $t_g(\omega)$, taken by the wave group to travel from the lightning source (the return stroke) to the receiver at range r is $r/v_g(\omega)$. Although this group travel time is frequency dependent, it not strongly so if we restrict measurement to frequencies well above the Earth-ionosphere waveguide cutoff of the dominant waveguide mode. From (3), $d\phi/d\omega$ is zero when $t = t_g(\omega)$. This means that the group travel time at frequency ω, namely $t_g(\omega)$, might be found on this criterion by trial and error. However it is simpler to measure $d\phi/d\omega$ at a single known time, t_0. Then

$$t_g(\omega) = t_0 - \frac{d\phi}{d\omega} \tag{4}$$

A sferic is detected at a receiver station when the voltage difference between two consecutive samples exceeds a threshold value, V_{th}. The 16 samples prior to detection and the following 48 (1 ms) are captured for processing. The sampling frequency and phase are precisely determined by the Global Positioning System (GPS) pulse-per-second (PPS) to determine the time of detection, t_0, to within a few hundred nanoseconds. This (t_0) is the time for use in (4). Since t_g is frequency dependent, we take the average value of t_g over the frequency range, 6–22 kHz to get the time of group arrival (TOGA). Lightning is located by the *difference* in arrival times at a pair of stations, so although the TOGA depends slightly on the frequency range chosen, the *difference* is essentially independent of the range chosen if it is the same for all stations. We chose this range because it is centred on the frequency of maximum amplitude (A in (1)) where, coincidentally, the group velocity in the dominant waveguide mode is the same (297 Mm/s) for day and night time propagation

SELECTING THE TOGAs FROM A COMMON LIGHTNING STROKE

The very long range of VLF propagation makes difficult the task of sorting the TOGA values returned from each (of eventually 12–20) station into sets due to common lightning strokes. This is because the average rate of sferics received at any one station is about 30/s, corresponding to an average time between sferics of about 33 ms, which is also the time for propagation over 10 Mm. To make matter worse, the sferic rate varies greatly about this average.

We currently adjust the detection threshold, V_{th}, to reduce detection of very distant, and so generally weaker, sferics. In most cases, the station which first detected a given lightning stroke is identified. This earliest TOGA is followed by the times of group arrival ("TOGAs") returned from the other stations. We can consider the TOGA data as a matrix of N columns, for a network of N stations, and an indefinite number of rows of progressively later TOGAs. We assume that all previous lightning strokes have been dealt with, and that the TOGAs used for their locations have been deleted from the matrix. Thus the earliest TOGA for the stroke under consideration is in the top row. Two tests or sifts are then applied to the TOGAs in the first few rows. We call these the "maximum TOGA difference" test and the "minimum TOGA sum test".

The first tests the TOGAs in the top row. All except the earliest TOGA are later than the earliest but each station's TOGA must not be later by more than the propagation time from the station of earliest TOGA to that station. This is best explained by an example. The 6 stations currently (April, 2002) in operation are Dunedin, Darwin, Perth, Osaka, Singapore and Brisbane. Suppose Darwin detected the stroke first, so its TOGA value is earlier than those for the other stations. The TOGA for Osaka is much later than the propagation time from Darwin to Osaka, so this TOGA must be that for a later lightning stroke. Therefore we add a blank cell, pushing down the entire "Osaka" column one row. We further suppose for illustration that there is no TOGA value in the Brisbane column because the Brisbane receiver is temporally out of operation. No action is taken on the "Brisbane" column which could be empty all the way down.

The top row now contains TOGA entries for Dunedin, Darwin, Perth, and Singapore, but blanks (no entry) for Osaka and Brisbane. If all previous lightning strokes have been dealt with, and the TOGAs used for their locations have been deleted, then all four TOGAs in the top row should be due to the same lightning impulse. However, the assumption may not be true (allowing a TOGA from an earlier stroke) or maybe a TOGA value is spurious (perhaps due to intense local noise from some temporary source), therefore we make the same test of the TOGA values in the second row, excluding the Darwin value in the second row since we are still using the Darwin value in the first row. We suppose that the Perth TOGA in the second row passes the test, so maybe this TOGA is the correct one for the stroke under consideration. For all the other stations in the second row, including Darwin, Osaka and Brisbane, we add a blank cell to each, pushing down each column one row. Thus the second row now contains only the second possibly valid TOGA for Perth. We can repeat this test for the third and later rows until there are no more possibly valid TOGAs. It is conceivable that a minutes-long burst of local intense noise continues to produce a spurious TOGA at Perth every few milliseconds. We suppose for this illustration that this did not happen (it has never happened so far), so the third row is empty after applying the first test ("maximum TOGA difference" test) to it and applying the actions made to the second row. We are left with one TOGA each for Dunedin, Darwin, and Singapore, and two TOGAs for Perth, all of which pass the first test but only one of the two for Perth can be real. The second test is to resolve the Perth ambiguity.

The second test is of no use if have one TOGA each for only four stations since four is the minimum number required for application of the location method. This location method is the downhill simplex method of successive approximations, itself a "second test" as we will see. The starting point is that of the station which detected the stroke first (Darwin in this example). For this and all later points in the iterative process, the group travel time from the point to each of the stations is calculated and compared with the observed TOGA. This gives the errors and the "downhill" direction for locations reducing the errors. This process continues until the RMS errors in successive iterations no longer decrease or if the number of iterations exceeds a preset number. Even if 100 iterations are required, current PCs can do this in a few milliseconds.

The downhill simplex method can be used for location in more than the two dimensions (latitude and longitude for lightning location) we require. For only one dimension (one variable) it is akin to least squares regression in that it works fine if the variable has only random errors. If we have only four points to fit by least squares, and one point is spurious (maybe orders of magnitude larger), the least squares fit is useless except for the error it returns to reveal that one (unidentified) point is spurious. Thus the downhill simplex method gives both the lightning stroke position and the likely error, with the latter revealing the inclusion of an (unidentified) TOGA either spurious or belonging to a different lightning stroke.

For the illustrative case considered above (one TOGA each for Dunedin, Darwin, and Singapore, and two TOGAs for Perth) there are only two possibilities to test, so we run the location method twice and return only the location giving the lesser error. Once the stroke location is made, the matrix rows involved (the top 3 in this case) are deleted and processing begun for the next stroke.

As we get progressively more sferic receiver stations in operation, the number of stations detecting a given lightning stroke will increase as will the number of stations returning more than one TOGA value satisfying the first test (the maximum TOGA difference test). The number of possible TOGA combinations would then be too large to test by the downhill simplex method in reasonable time, so we use the "minimum TOGA sum test." This is based on the fact that the lightning stroke must occur near the surface of the Earth, not megametres above or below it. It works best when many widely spaced stations detect the same lightning stroke, for regardless of the location of the lightning stroke, there is a minimum spread in the TOGAs. This is expressed as the sum:

$$\sum_{j=1}^{N}\left(T_j - T_0\right) \tag{5}$$

where N is the number (less one) of stations detecting the lightning stroke, T_0 is the TOGA logged by the station of first detection, and the T_j are the TOGAs logged by the other stations for the set under test. This sum depends on the stroke position, though not strongly, so we use the minimum value for each station of first detection. These minimum values are shown in Table 1 (next page). Each column is headed by the station which detected the lightning stroke first. The first data row gives the minimum of the sum defined by (5) for the our current network of 6 stations when a stroke is detected by all 6 (so N = 5). The rows below this apply when only 5 of the 6 stations detect the stroke. For example, suppose a stroke is detected first by Darwin, and then (not in this order) by Dunedin, Perth, Singapore and Brisbane, but is not detected by Osaka. The yellow highlighted entry in the Table shows that the sum defined by (5) should have been at least 16.6 ms. If the sum is less than this, at least one of the TOGAs is due to an earlier stroke or is spurious. If only four stations detect the stroke, this minimum TOGA sum test is of no use since four is the minimum for location by the downhill simplex method (which is itself the best test of a common lightning stroke), so there is no choice. In any case, for some combinations of four stations, the minimum TOGA sum is too small to be a test.

Table 1. Minimum TOGA sums for detection by all six stations (top data row) or only five (other data rows).

Earliest station	Dunedin	Darwin	Perth	Osaka	Singapore	Brisbane
Detected by all	40.3 ms	24.0 ms	34.7 ms	24.1 ms	35.2 ms	23.9 ms
not Dunedin	————	16.7 ms	22.6 ms	16.5 ms	17.8 ms	17.1 ms
not Darwin	35.5 ms	————	14.8 ms	11.5 ms	11.9 ms	11.6 ms
not Perth	19.9 ms	15.5 ms	————	15.4 ms	27.0 ms	15.4 ms
not Osaka	18.0 ms	16.6 ms	16.8 ms	————	24.4 ms	16.6 ms
not Singapore	27.4 ms	15.9 ms	25.0 ms	15.7 ms	————	15.7 ms
not Brisbane	16.6 ms	16.8 ms	27.1 ms	17.9 ms	26.4 ms	————

The map below (Fig. 1) shows lightning stroke plots which are updated every 10 minutes. The region displayed is that for adequate location accuracy with only six stations at the time of writing (deadline for this "paper").

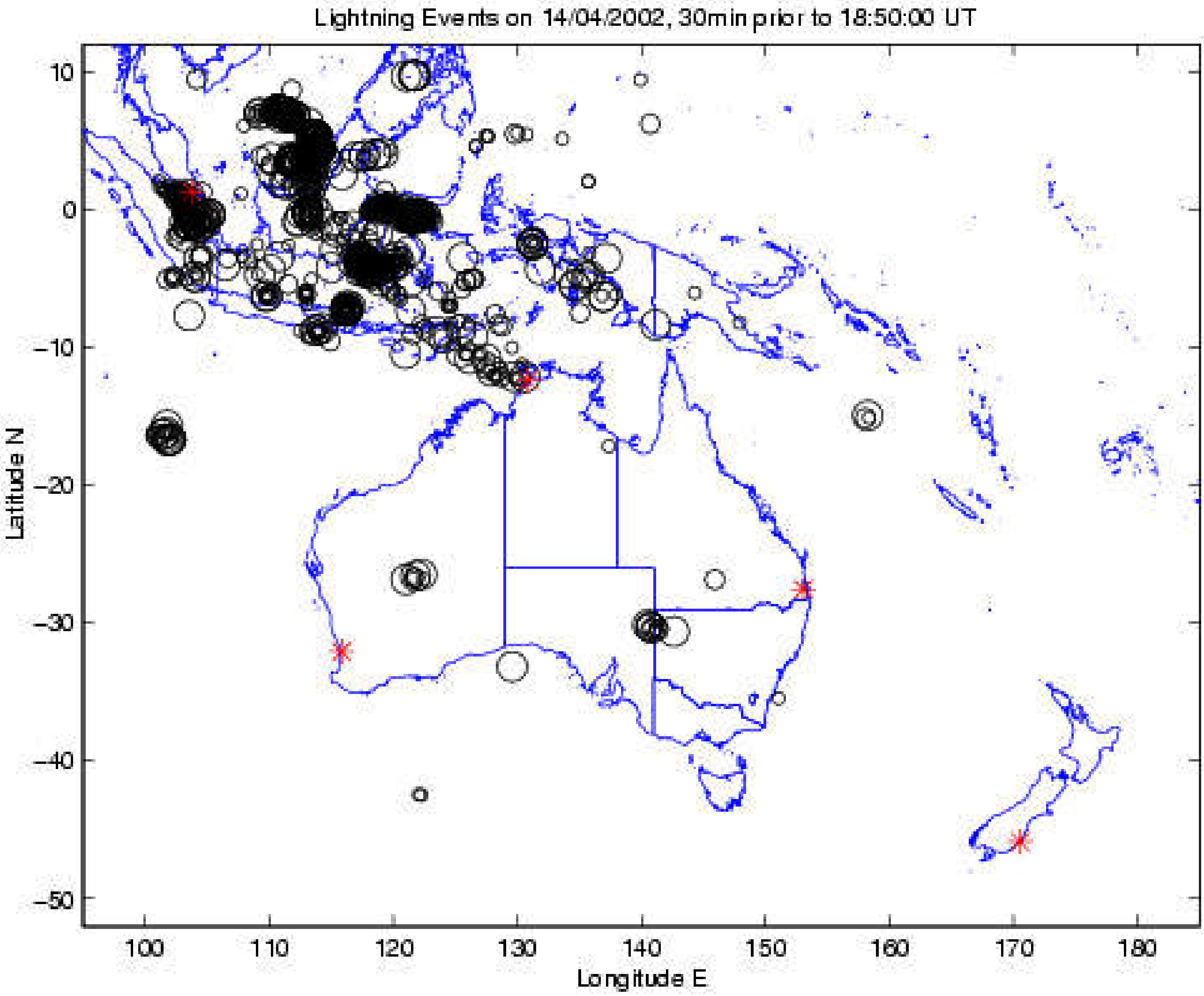

Fig. 1. Map down loaded from our web site: http://ritz.otago.ac.nz/~sferix/TOGA_network_Oz_maps.html. The largest circles indicate the positions of most recent strokes (those between 18:40 UT and 18:50 UT). The medium size circles show those occurring between 18:30 UT and 18:40 UT, and the smallest circles show those between 18:20 UT and 18:30 UT. Local time at longitude 120º E (where most of the strokes were occurring) was 02:50 on 15/04/2002 at 18:50 UT. The red asterisks mark the locations of (clockwise from bottom right) Dunedin, Perth, Singapore, Darwin and Brisbane.