Faraday Rotation and L-band Oceanographic Measurements

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Abstract

Spaceborne radiometric measurements of the L-band brightness temperature over the oceans enables a determination of sea salinity. However, Faraday rotation in the ionosphere complicates matters, and must be corrected for. Two different ways of assessing the rotation directly from the radiometric measurements, and hence correct for the effect, are discussed. Also, a method, that totally circumvents the problem by using the first Stokes parameter in the salinity retrieval, is discussed.

1. Background. The SMOS project

Significant progress in weather forecasting, climate monitoring, and extreme event forecasting, depends on accurate quantification of both soil moisture and sea surface salinity.

It has for some time been known that a spaceborne L-band (1.4 GHz) radiometer system is able to provide the necessary data from which soil moisture and sea salinity can be retrieved. However, such systems traditionally require massive antenna structures. For this reason there has not been and currently is no capability for directly and globally estimating these key variables, and it is in response to this fact, that SMOS has been proposed and selected as an ESA Earth Explorer Opportunity Mission.

SMOS is a 1.4 GHz two-dimensional interferometric radiometer system with 72 antenna elements and radiometers on three 4.2 m long arms. In the central unit 2556 correlators are found. The system acts as a radio camera, and as the satellite moves forward, a wide swath is covered – without mechanical movement. The ground resolution is comparable to that associated with a filled aperture having a radius equal to an arm length. Less structure, hence weight, is evident, and the arms are easily folded for integration with a modest sized launcher. SMOS will enable global measurement of soil moisture to the 0.04 m^3/m^3 level with 50 km ground resolution, and, after suitable integration, sea salinity to the 0.1 psu level with a 200 km ground resolution.

The most difficult measurement, seen from a radiometer technology point-of-view, is the salinity assessment, and only this subject will be dealt with in the following.

The L-band brightness temperature (T_B) of the ocean depends on salinity (S), which is of course the effect we intend to utilize, but there is also significant dependence on sea surface temperature (SST) and wind speed (WS). The following considerations concern vertical polarization (V pol) and 50° incidence angle unless otherwise indicated.

The brightness temperature sensitivity to salinity is at best (open, warm ocean) approaching $\Delta T_B / \Delta S = 1K / psu$. Hence, to find salinity to the 0.1 psu level requires radiometric measurements to better than 0.1 K *and* knowledge concerning the influence of other effects to the same level.

2. The Faraday rotation

Normally, within radiometry, ionospheric effects are ignored, but in the present case the frequency is so low and the measurement requirements so stringent that an investigation is necessary.

The plane of polarization of microwave signals propagating from Earth through the ionosphere to a satellite is rotated by an angle θ. The amount of rotation depends on the direction and location of the ray path with respect to the Earth's geomagnetic field, and on the state of the ionosphere. To get a feeling for the magnitude of the polarization rotation, a mean daytime value of θ can be estimated from:

$$\theta = 17/F^2 \text{ (F in GHz)} \qquad (1)$$

Hence, the average daytime rotation is found to be $\theta = 8.7^\circ$ at 1.4 GHz.

A more in-depth treatment of the Faraday rotation is found in [Svedhem, 1986]. From this, Figure 1 is taken, and it shows the worst case average rotation on 12.00 UTC March equinox. Incidence angle here and in the following is 50°. Daytime maximum average (monthly average) rotation is predicted to 28°, whereas maximum averaged morning (6.00 AM) values are around 5°. In addition, day to day variations can reach values within +100% to -50% of the averaged values due to the unpredictable nature of the ionosphere.

SMOS will have a 6 AM orbit, so from these considerations it is clear that the radiometer system has to cope with at least 5°, possibly up to 10°, Faraday rotation.

The polarization rotation will result in a slight mixing of the true vertical (T_{BV}) and horizontal (T_{BH}) brightness temperatures. The radiometer will measure:

$$
\begin{aligned}
T_{BV}^{\copyright} &= T_{BV} \cdot \cos^2 \theta + T_{BH} \cdot \sin^2 \theta \\
T_{BH}^{\copyright} &= T_{BV} \cdot \sin^2 \theta + T_{BH} \cdot \cos^2 \theta
\end{aligned}
\qquad (2)
$$

Typical values are $T_{BV} = 132$ K and $T_{BH} = 66$ K.

Assuming $\theta = 10^\circ$ we find:

$T_{BV}^{\copyright} = 130.0$ K and $T_{BH}^{\copyright} = 68.0$ K

The 2 K error in T_{BV} translates into an error in retrieved salinity of some 2-4 psu (depending on sea temperature) which is totally unacceptable.

3. Correction based on polarization ratio

The set of equations (2) can be solved with respect to T_{BV} for example. After some reductions the following expression is found:

$$T_{BV} = \frac{T'_{BV} - T'_{BH} \cdot tg^2\theta}{1 - tg^2\theta} \qquad (3)$$

Hence, if both the local vertical (T'_{BV}) and horizontal (T'_{BH}) brightness temperatures are measured, and θ is known, the true vertical brightness temperature can be found.

The true and the local polarization ratios are defined as:

$$\begin{aligned} R &= \frac{T_{BV}}{T_{BH}} \\ R' &= \frac{T'_{BV}}{T'_{BH}} \end{aligned} \qquad (4)$$

Inserting the expressions for the local brightness temperatures into the expression for the local polarization ratio, leads after some reductions to the following expression for the angle of rotation:

$$tg^2\theta = \frac{R - R'}{R \cdot R' - 1} \qquad (5)$$

Hence, if the true polarization ratio is known, the Faraday rotation can be found from measurements of the local polarization ratio.

From a model for the brightness temperature of the sea based on [Klein & Swift, 1977], including the Hollinger wind responses (0.2 K per m/sec at V pol and 0.3 K per m/sec at H pol), summarized in [Sasaki et al, 1987], the curves in Figures 2 through 4 have been generated. Figure 2 shows the basic vertical brightness temperature sensitivity to salinity and sea surface temperature. From Figure 3 it is seen that the true polarization only exhibits a marginal dependence on salinity and temperature: R varies between 2.00 and 2.09 if we include the complete 0 - 30° range in temperature and 0 - 38 psu in salinity.

The variations are typically much less for realistic conditions where we know ballpark temperature and salinity figures for a given area. If we for example restrict the situation to cover 21 ± 1 °C & 35 ± 1 psu, we find that R varies between 2.061 and 2.068 corresponding to a 0.3 % variation.

Figure 4 shows a stronger dependence on wind speed with variations from 2.06 down to 1.94 for realistic wind speeds between 0 and 20 m/sec (20 °C & 34 psu), i.e. a 6 % variation.

So, if the wind speed is known, the true polarization ratio (R) can be estimated with good fidelity. By measuring the local ratio (R'), θ can then be found and finally having this, the true vertical brightness temperature is found using the formulas shown above. Similarly the true horizontal brightness temperature may be found.

Simple example with no measurement errors

Consider the following example:

- S = 34 psu
- SST = 20 °C
- WS = 10 m/sec.

From the ocean model is then found:

- T_{BV} = 132.65 K
- T_{BH} = 66.40 K
- R = 1.998

We further assume a 10 ° Faraday rotation, and the measured (local) brightness temperature values are found to be:

- T'_{BV} =130.65 K
- T'_{BH} = 68.40 K

If we used these figures without correcting for the Faraday rotation, the retrieval would (not surprisingly) run into serious trouble. The H-pol figure points towards *lower* salinity while the V-pol figure points towards *higher* salinity (bearing in mind that we steadily assume that we know the wind speed from other sources). Considering Faraday rotation, we note that the measured local polarization ratio is R' = 1.910. Using equation (5) we then find $\theta = 10.02°$ and from (3):

- T_{BV} = 132.65 K

meaning that the correct value of the 1.4 GHz vertical brightness temperature is recovered, and good quality geophysical parameters may be found.

The example is only a quick illustration of the retrieval procedure excluding radiometric and other errors. In the following some of these will be included.

Example with radiometric errors

A simple sensitivity analysis has been carried out to see what happens when radiometric errors of ± 0.1 K are considered. For the ocean conditions: 34 psu salinity, 20 °C temperature, 10 m/sec wind speed, and 10° & 3° Faraday rotation, the following is calculated: modeled vertical and horizontal brightness temperatures, polarization ratio, and resulting local vertical and horizontal brightness temperatures. These are then perturbed ± 0.1 K. This gives a total of 8 possibilities per Faraday angle (including the case without perturbation). Using these more or less wrong values, the associated local polarization ratio, the retrieved Faraday angle, and finally the retrieved vertical brightness temperature are calculated. The result is that the Faraday angle and the brightness temperature are found quite well despite the radiometric errors: the average error in the retrieved vertical brightness temperature is 0.07 K (worst case: 0.13 K). The observed errors in the brightness temperature are largely due to propagation of the measurement errors - not due to incorrect Faraday correction: once you have measured a certain brightness temperature wrongly due to instrument errors, you cannot find the true value.

Example with error in S and/or SST assessment

As already discussed a realistic scenario might be that the we know that the sea temperature is for example 21 ± 1 °C and the salinity 35 ± 1 psu. The nominal polarization ratio R is then 2.065 with a variation between 2.061 and 2.068 as already stated. If we in the retrieval process as described above use the nominal value for R but in fact the salinity and/or the temperature were off by one unit, we make an error as the true polarization ratio may be off by on average 0.002. This gives an error on the retrieved vertical brightness temperature of 0.04 K which is acceptable.

Example with error in wind speed assessment

Finally, it is checked what happens if there is no instrument errors nor errors in the S and SST assessment, but we have assessed the wind speed wrongly. The true wind speed is once again 10 m/sec which gives us the usual vertical and horizontal brightness temperatures, hence polarization ratio. Using this information we of course (as in the first simple example) retrieve the correct Faraday angle hence vertical brightness temperature. But if our measurement of wind speed wrongly indicates 8 m/sec, Figure 4 gives us a wrong "true" polarization ratio, which in turn gives a wrong Faraday angle, hence an incorrect retrieved brightness temperature being off by 0.22 K. Good wind speed data seems crucial.

4. Correction based on polarimetric measurements

Until now it has been assumed that the radiometer system in question measures only the traditional vertically and horizontally polarized signals. If, however, the radiometer is enhanced to be a fully polarimetric system, new possibilities arise. The (brightness) Stokes vector is:

$$\overline{T}_B = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} T_V + T_H \\ T_V - T_H \\ T_{45^\circ} - T_{-45^\circ} \\ T_l - T_r \end{pmatrix} = \frac{\lambda^2}{k \cdot z} \begin{pmatrix} \langle E_V^2 \rangle + \langle E_H^2 \rangle \\ \langle E_V^2 \rangle - \langle E_H^2 \rangle \\ 2 \ \mathrm{Re} \ \langle E_V E_H^* \rangle \\ 2 \ \mathrm{Im} \ \langle E_V E_H^* \rangle \end{pmatrix} \qquad (6)$$

The first Stokes parameter I is the sum of the vertical and horizontal brightness temperatures (i.e. represents the total power in the field) while the second Stokes parameter Q is the difference of the same quantities. It is seen that I and Q represents the information also found in the traditional V and H polarized radiometer. The third Stokes parameter can be interpreted as either the real part of the correlation between the vertical and horizontal electrical fields, or as the difference between orthogonally sensed brightness temperatures skewed 45° with respect to the normal vertical and horizontal orientation. Finally, the fourth Stokes parameter is interpreted as either the imaginary part of correlation between the vertical and horizontal fields, or as the difference between left-hand and right-hand circularly polarized brightness temperatures.

Subjected to a Faraday rotation θ, the Stokes parameters, as sensed by the polarimetric radiometer system, can be expressed in terms of the true parameters:

$$\begin{aligned} I' &= I \\ Q' &= Q \bullet \cos 2\theta + U \bullet \sin 2\theta \\ U' &= -Q \bullet \sin 2\theta + U \bullet \cos 2\theta \\ V' &= V \end{aligned} \qquad (7)$$

It is seen that the first Stokes parameter is unaffected by Faraday rotation, which is not surprising bearing in mind that it represents the total power in the field, and power is not affected by a rotation. Likewise, the fourth parameter, being based on circular polarized quantities, is of course unaffected. Now, the interesting Stokes parameter in the present context is the third, U. The locally sensed U' firstly contains the natural third Stokes parameter, and for small Faraday rotations with a weight of almost 1 due to the cosine factor. But U' also contains a contribution from the difference between the natural vertical and horizontal brightness temperatures, strongly dependent of the Faraday rotation angle due to the sinus factor. Taking again the typical numbers from Section 2, T_{BV} = 132 K and T_{BH} = 66 K, meaning that Q = 66 K, we find a contribution for $\theta = 10^\circ$ as large as 23 K. The natural third Stokes parameter value for the ocean may at the time of writing not yet be fully established, but it generally agreed that it is small: below 1 K and possibly only a tenth of that. This means that in the present context we may ignore it, and having measured Q' and U' the Faraday angle can with good fidelity be found from the equations (7). This concept has first been published and discussed by [Yueh, 2000].

Having found the Faraday rotation angle the true vertical brightness temperature is found using (3).

5. Avoiding the problem by using the first Stokes?

It has been discussed in Section 3 that by measuring H & V polarization and assuming knowledge of the wind speed, the Faraday rotation can be estimated and corrected for by investigating polarization ratios.

Likewise, it has been discussed in Section 4 that if the fully polarimetric signal (all 4 Stokes parameters) were measured, and azimuthal symmetry of the scene is assumed (i.e. very little natural third and fourth Stokes signals) the Faraday rotation can be assessed and hence corrected for.

However, the fully polarimetric mode is not the SMOS baseline mode, but it may be proposed that one might circumvent the whole Faraday problem by retrieving the necessary geophysical parameters from the first Stokes parameter alone as this is not affected by the rotation. The following discusses this retrieval option by checking the sensitivity of I to relevant geophysical parameters: salinity, temperature, and wind speed.

Figure 5 shows how the first Stokes parameter depends on sea temperature in the no-wind condition.

For open, warm ocean, 20 °C and in the 30 - 38 psu range, we observe a first Stokes parameter sensitivity to salinity of:

- $\Delta I/\Delta S = 1.10$ K/psu

This must be compared with the sensitivity of the vertical brightness temperature to salinity which is found to be (Figure 2):

- $\Delta T_{BV}/\Delta S = 0.69$ K/psu

The sensitivity of the first stokes parameter compares well with that of the vertical brightness temperature. The radiometric sensitivity associated with the first Stokes parameter is inherently a square root of 2 worse than that of the vertical brightness temperature, and 0.69 K x 1.41 = 0.98 K, i.e. smaller than 1.10 K.

For cooler open ocean, 10 °C and in the 30 - 38 psu range, we find for the first Stokes:

- $\Delta I/\Delta S = 0.75$ K/psu

which again compared well with the sensitivity of the vertical brightness temperature:

- $\Delta T_{BV}/\Delta S = 0.47$ K/psu

Finally, for cold open ocean, 0 °C and in the 30 - 38 psu range, we find for the first Stokes:

- $\Delta I/\Delta S = 0.45$ K/psu

which again compared well with the sensitivity of the vertical brightness temperature:

- $\Delta T_{BV}/\Delta S = 0.28$ K/psu

Also, the sensitivity to sea surface temperature can be assessed. As usual, the sensitivity is very small around 30 psu. For 38 psu and the 20 - 30 °C range we find:

- $\Delta I/\Delta\ SST = 0.29$ K/ °C

for the first Stokes parameter, while the sensitivity for the vertical brightness temperature is:

- $\Delta T_{BV}/\Delta SST = 0.16$ K/ °C

The ratio $\Delta I/\Delta T_{BV}$ is slightly larger for the temperature sensitivity than for the salinity, i.e. an unwanted feature, but the difference is small and the knowledge of sea surface temperature from other sources so good that this is not considered a show-stopper.

Finally, the sensitivity to wind speed must be assessed. For the time being we must rely on the old Hollinger data, which predicts 0.2 K/m/sec for V pol and 0.3

K/m/sec for H pol at 50 ° incidence angle. This means that the sensitivity of the first stokes parameter to wind speed is assessed to:

- $\Delta I/\Delta WS = 0.5$ K/m/sec

which unfortunately is a factor 2.5 larger than that concerning normal vertical brightness temperature. $\Delta I/\Delta S$ was typically a factor 1.6 larger than $\Delta T_{BV}/\Delta S$, i.e. in relation to the wind speed we are a factor 2.5/1.6 = 1.6 worse off. However, other incidence angles have other sensitivities, the old wind data can be questioned, and updates are underway (WISE Campaign, see later). Furthermore, there is a not straightforward trade off between using a retrieval independent of Faraday rotation problems and some sensitivity to wind - and a retrieval that have to deal with uncertainties in relation to Faraday and a slightly smaller sensitivity to wind speed.

In conclusion, it seems that a more in-depth investigation of the merits of a retrieval of salinity based on the first Stokes parameter is highly warranted.

6. Other incidence angles and wind speed dependencies

All considerations until now have been carried out with a 50° incidence angle - a quite typical value for Earth sensing satellite systems. However, this value is not necessarily the optimum choice for a future L-band ocean mission, be it a real aperture of a synthetic aperture system. Indeed, the SMOS system will sense a full range of incidence angles from nadir to beyond 50°. So, it is if interest to assess to which degree the results discussed until now also holds for other angles. In the following a 30° incidence angle is assumed.

Again the Klein & Swift model has been run, and results are displayed as Figures 6 - 8. The basic vertical brightness temperature sensitivity to salinity (open, warm ocean: 20° C & 30 - 38 psu) is now

- $\Delta T_{BV}/\Delta S = 0.60$ K/psu

in contrast to the original 0.69 K/psu, i.e. a slight sensitivity reduction. The same tendency is found for cooler water.

The sensitivity to sea surface temperature is practically the same as it was at 50° incidence.

The polarization ratio and its relative variation with temperature and salinity is much smaller than before. For the realistic example 21 ± 1 °C & 35 ± 1 psu, we find that R undergoes a 0.16 % variation, in contrast to the original 0.3 % variation. This means that the assessment of sea temperature and salinity becomes less demanding when trying to assess the true polarization ratio.

The Hollinger wind data indicates wind responses of 0.25 K per m/sec at both polarizations (30° incidence angle). This of course means that to first order the polarization ratio does not change with wind speed, greatly simplifying the task of assessing the true polarization ratio.

Again, the exercise: example with radiometric errors in Paragraph 3 has been carried out, and the average error in the retrieved brightness temperature is now 0.06 K where it was 0.07 K before.

All in all, the correction method based on the polarization ratio works better at steeper incidence.

Going to Figure 8 we find for the first Stokes parameter sensitivity to salinity (open, warm ocean: 20° C & 30 - 38 psu) :

- $\Delta I/\Delta S = 1.09$ K/psu

which is practically as before. Likewise for cooler water.

The sensitivity to sea surface temperature is practically the same as it was at 50° incidence.

The wind speed dependence for the vertical brightness is 0.25 K / m/sec, and for the first Stokes it is 0.5 K / m/sec i.e. a factor 2 larger. At 50° incidence this factor was 2.5, so we are now better off.

All in all, the use of the first Stokes parameter works as good or better at steeper incidence.

Finally, it must be noted that the brightness temperature dependence on wind speed has played a rather significant role in the discussions. The old Hollinger values have been quoted and used: 0.25 K per m/sec for both vertical and horizontal polarization up to some 30° incidence whereupon the curves diverge, and at 50° incidence we find 0.2 K per m/sec at V pol and 0.3 K per m/sec at H pol. Recent measurements in the WISE campaign [Camps et al, 2001] seems to indicate the same sensitivity (again 0.25 K per m/sec) for both polarizations up to some 45° incidence whereupon the curves starts to diverge. In this case the retrieval based on the polarization ratio correction method will be more attractive, as the wind speed assessment need to be less stringent (for assessing Faraday rotation, that is. The basic correction of the brightness temperature for wind speed dependence is of course still an important issue for any retrieval of salinity).

7. Conclusions

It is well established that important sea surface parameters can be remotely sensed by a spaceborne L-band radiometer. Vertical polarization is sensitive to salinity, and presently several missions are discussed in order to measure this important parameter - foremost the SMOS mission which is already an established ESA program. However, Faraday rotation will mix the horizontally and vertically polarized signals emitted from the sea surface as they are received by the radiometer. But if the Faraday rotation is known and the radiometer measures the local horizontal and vertical signals, the mixing can be untangled and the true vertical brightness temperature recovered for the salinity algorithms to work. The price to pay is that a dual polarized radiometer is needed despite the fact that we really only need the true vertically polarized brightness temperature - and we need to know the Faraday rotation angle. This might be available from external sources, but this option is not discussed here. The issue here is to try and get around the problem without additional external information.

Firstly, it is demonstrated that by using the local polarization ratio (vertical divided by horizontal brightness signal) and assessing the true polarization ratio, the Faraday angle can be found. The true polarization ratio can be assessed if the wind speed is known from some external source - which is needed anyway in the basic salinity retrieval process.

Secondly, the Faraday angle can be assessed by enhancing the radiometer to full polarimetric operation. Assuming a small natural third Stokes parameter value for ocean surfaces, the measured value will enable recovery of the Faraday angle. The additional price to pay is of course the complexity of polarimetric operation of the radiometer. The baseline mode for SMOS is not polarimetric.

Thirdly, the Faraday problem can be totally circumvented by directly retrieve salinity from the first Stokes parameter which is insensitive to rotation. The price to pay is that the L-band brightness temperature is slightly more dependent on sea surface temperature and wind speed than what was the case for the traditional vertically polarized signal, which makes them more difficult to correct for.

During the design phase of a radiometer system it must be decided whether to go for the second option as this has severe hardware implications. But note that an early choice between the first and the third option is not needed. In the data retrieval phase after launch the optimum option can be selected as demanded by the situation.

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Figure captions

Figure 1. One way Faraday rotation in degrees at 1.4 Ghz for March equinox, 12.00 UTC. Ground incidence angle 50°, azimuth worst case.

Figure 2. Vertical brightness temperature (TV) as a function of sea surface temperature (SST) with salinity as parameter. Wind speed is zero.

Figure 3. Polarization ratio (R) as a function of sea surface temperature (SST) with salinity as parameter. Wind speed is zero.

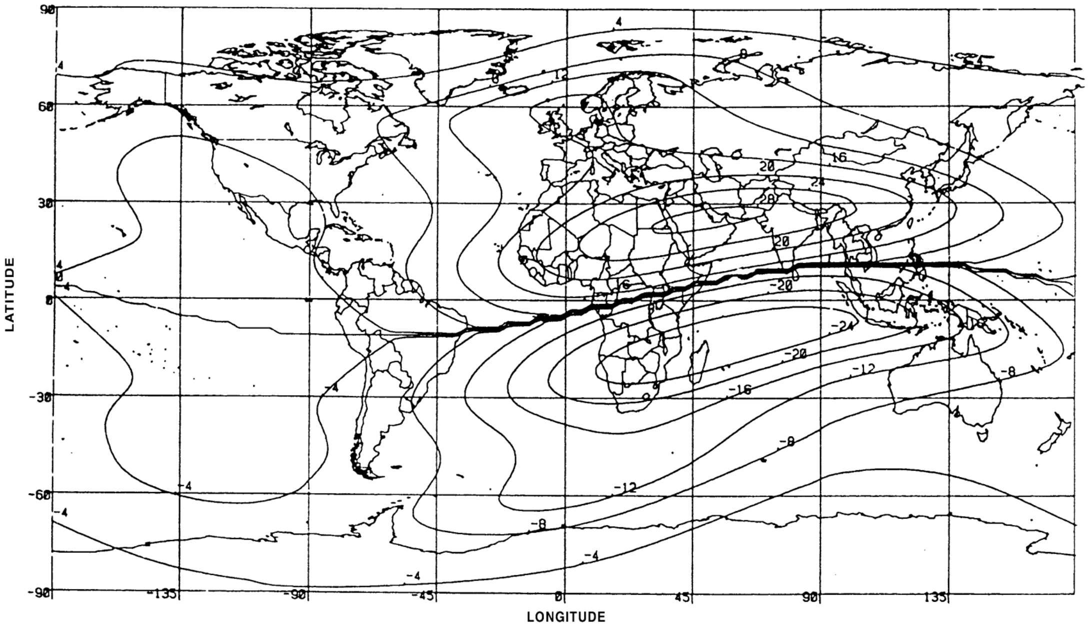
Figure 4. Polarization ratio (R) as a function of wind speed (WS) with sea surface temperature as parameter. Salinity is 34 psu.

Figure 5. First Stokes parameter (I) as a function of sea surface temperature (SST) with salinity as parameter. Wind speed is zero.

Figure 6. Vertical brightness temperature (TV) as a function of sea surface temperature (SST) with salinity as parameter. Wind speed is zero. 30° incidence.

Figure 7. Polarization ratio (R) as a function of sea surface temperature (SST) with salinity as parameter. Wind speed is zero. 30° incidence.

Figure 8. First Stokes parameter (I) as a function of sea surface temperature (SST) with salinity as parameter. Wind speed is zero. 30° incidence.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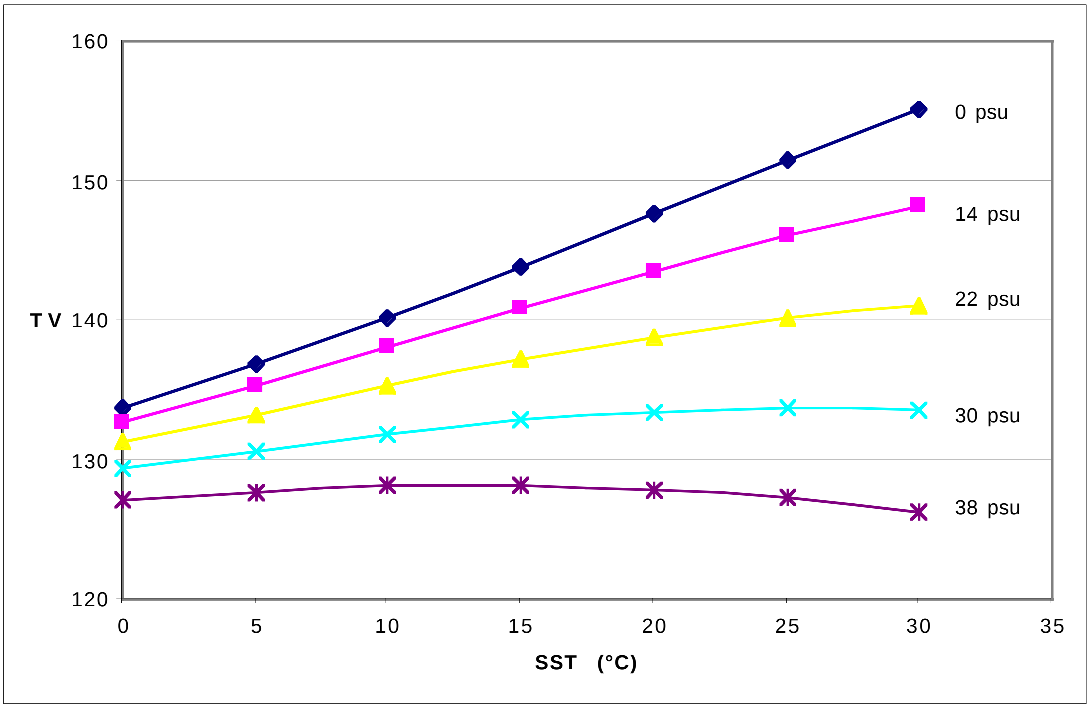
LONGITUDE

Fig 1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SST (°C)
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Fig 2

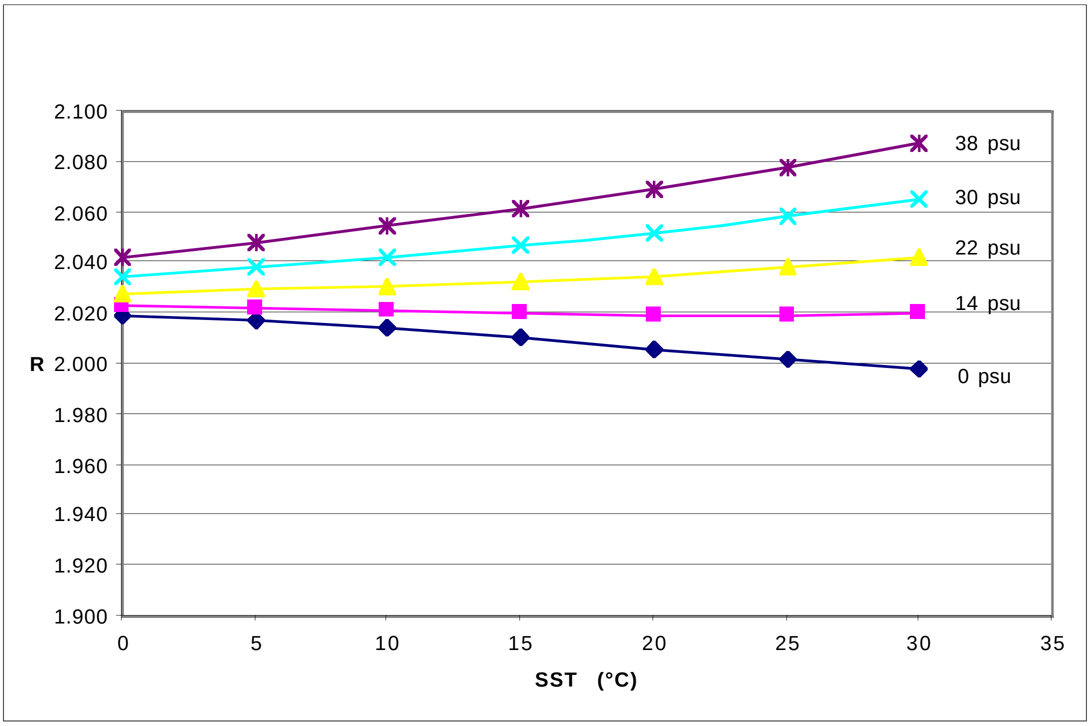
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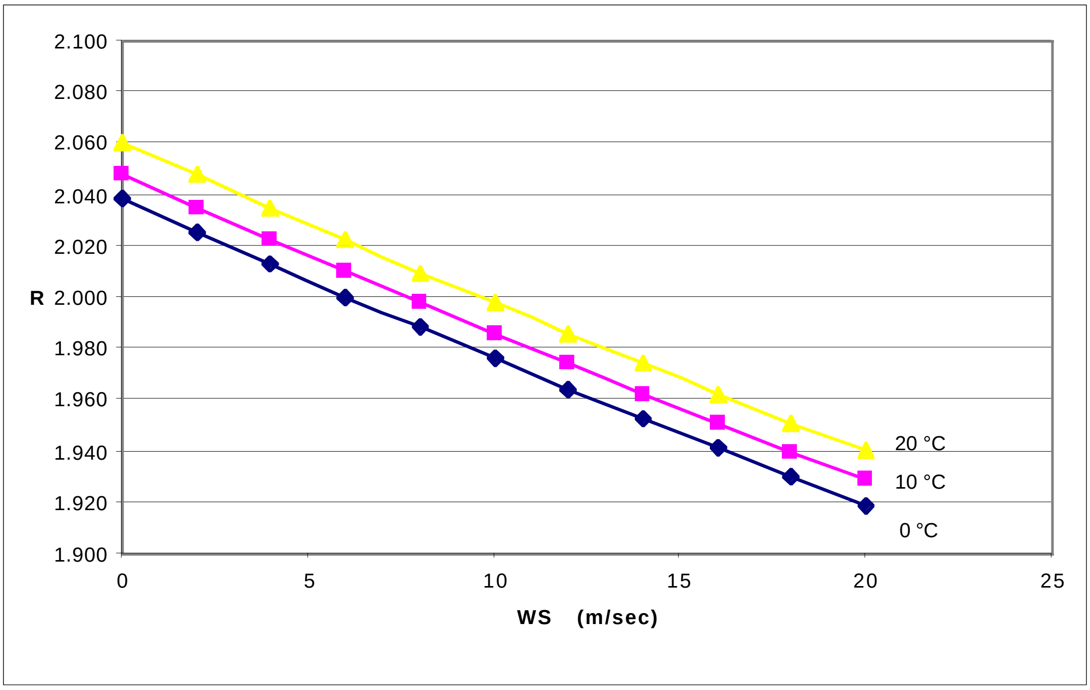
Fig 3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WS (m/sec)
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10 °C
0 °C

Fig 4

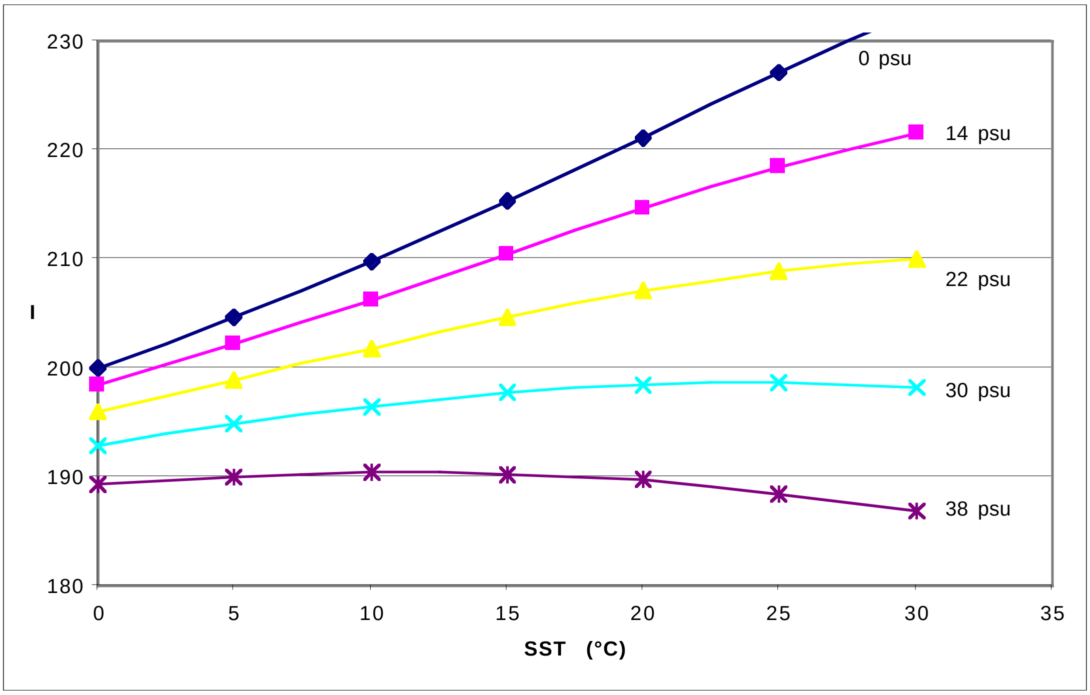
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Fig 5

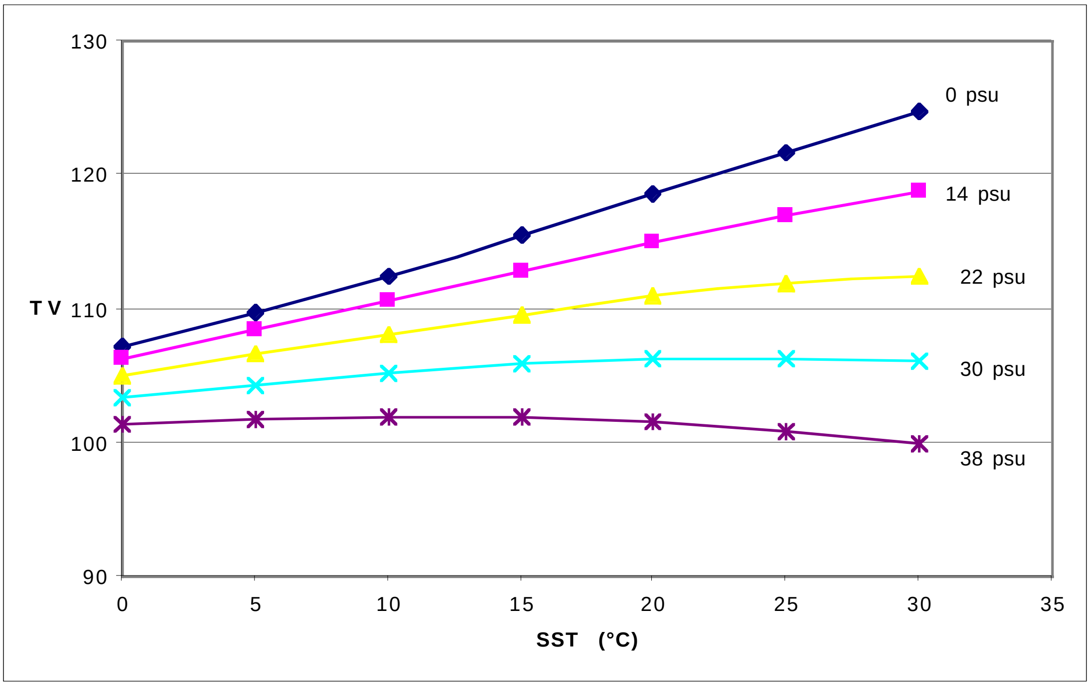
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Fig 6

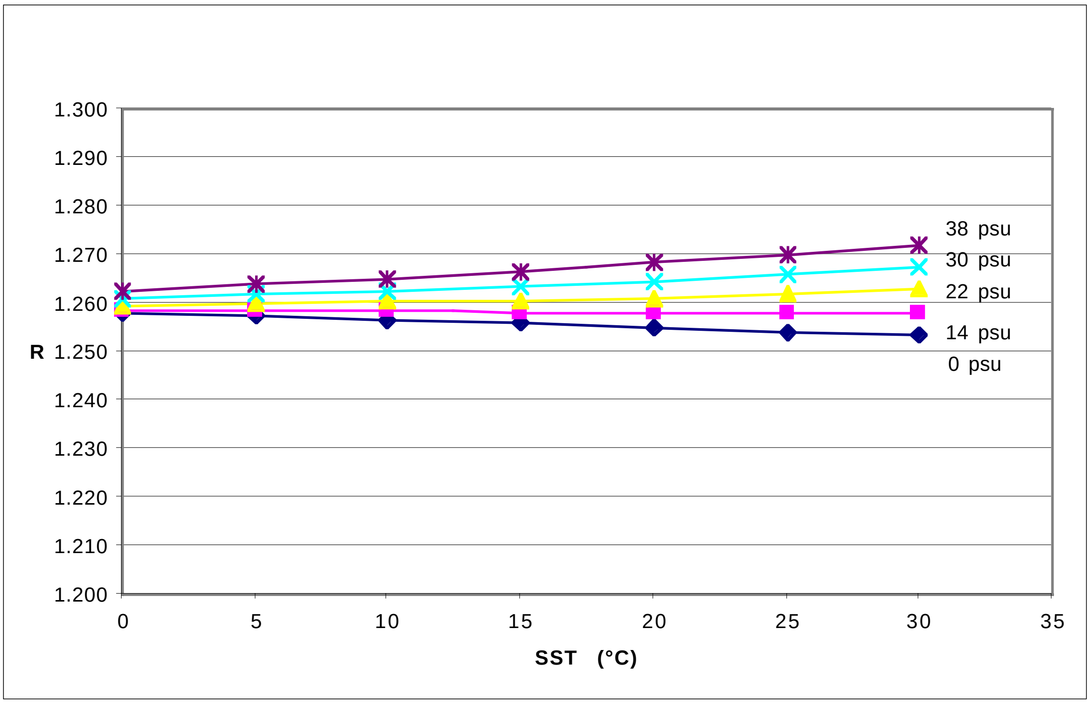
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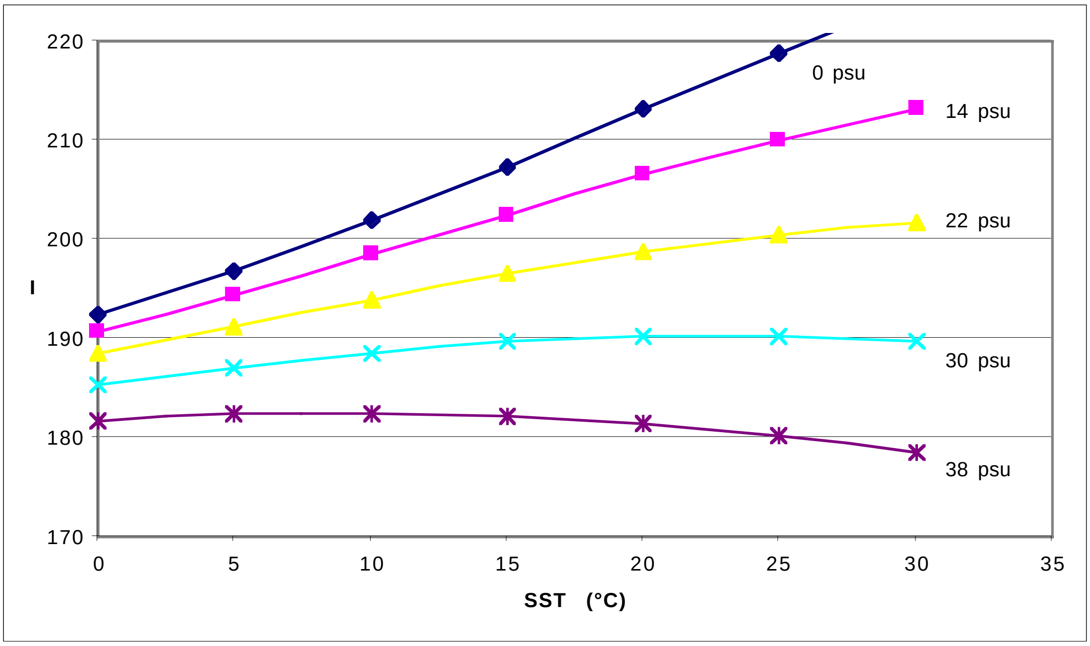
Fig 7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SST (°C)
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30 psu
38 psu

Fig 8