RECENT DEVELOPMENTS IN ICE AND WATER COLUMN PROFILING TECHNOLOGY

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ABSTRACT

Summaries of SWIPS technology and results and recommendations of a 2004-2005 field river ice monitoring program in the Peace River are provided preparatory to description of an expanded 2005-2006 field program. Preliminary results from this program and from accompanying analytical and theoretical studies are described and related to the capabilities of the latest generation of the SWIPS instrument.

KEY WORDS: River ice; Frazil ice, upward-looking sonar profiling**.**

INTRODUCTION

In September, 2005 a report presented to a conference sponsored by the CGU HS Committee on River Ice Processes and the Environment in Hanover, NH (Jasek et al., 2005) described results from an initial deployment of ASL's Shallow Water Ice Profiler Sonar (SWIPS) on the Peace River in Alberta, Canada. Although the instrument was originally developed for near-realtime or realtime monitoring of marine ice draft from shoreline facilities, the Peace River deployment explored the feasibility of obtaining similar information on winter river ice regimes. The testing demonstrated SWIPS capabilities for establishing ranges to the floating river ice cover's undersurface and interior features as well as for profiling acoustic backscatter in the underlying water column. The obtained results allowed detailed observation of the dynamic processes involved in the development, stabilization, deterioration and eventual break-up of a river ice cover. Moreover, the technology appeared to offer prospects for both detection and characterization of suspended frazil ice. Fuller exploration of these possibilities was found to require additional understandings of ice and river properties as well as instrument improvements to enhance sensitivity to frazil ice scatterers and eliminate interruptions of data collection by accumulations of anchor ice.

Considerable progress has been made since the Jasek et al. (2005) presentation through both theoretical studies of underlying acoustic issues and a second Peace River deployment which incorporated additional use of a second, similar, instrument operating at a higher acoustic frequency. Preliminary results from these efforts will be described below after: brief descriptions of the SWIPS instrument; a summary of the 2004-2005 season results; and an outline of the issues addressed in 2005-2006 field and analytical efforts.

SWIPS TECHNOLOGY IN RIVER APPLICATIONS

The basic concept of the SWIPS approach to ice cover and water column monitoring draws on ASL's well-developed deep water Ice Profiling Sonar (IPS) technology to achieve economies of cost and risk allowed by applications in shallower water and in proximity to shoreline installations. Specifically, shallower water allows use of less expensive broader beam transducers while near-shoreline locations avoid the necessity for putting expensive, vulnerable components in an underwater environment and offer immediate access to data and capabilities for changing measurement parameters. A typical river SWIPS installation is illustrated in Figure 1.

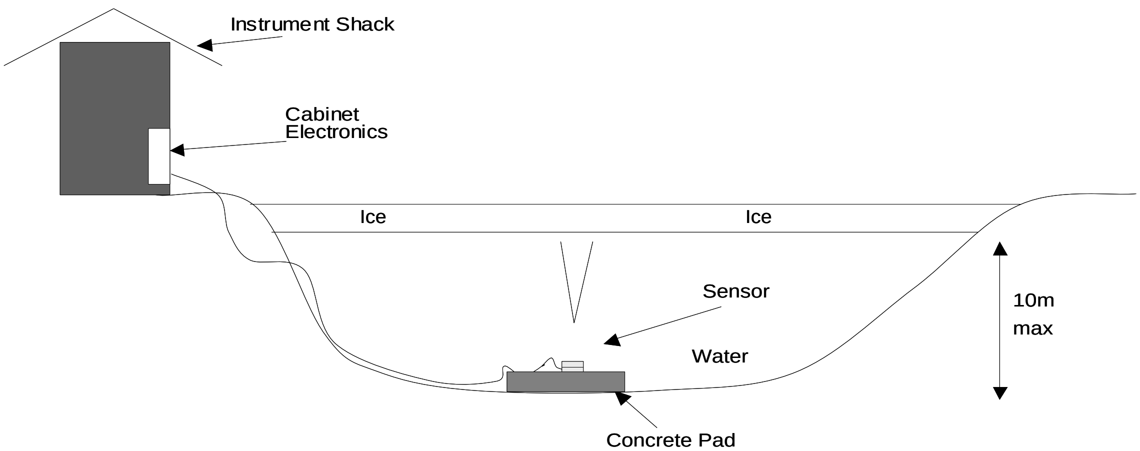

Figure 1. Sketch of Peace River test deployment configuration.

The underwater portion of the SWIPS is mounted on a waterproofed concrete block affixed to the river bottom and linked to an adjacent instrument shack about 100 m away by a 6-conductor cable). Underwater components in the 2004-2005 deployment included a commercial grade 235 kHz ceramic transducer, a thermometer and a two axis tilt sensor potted in a PVC container attached to a 50 lb concrete block. The transducer incorporated a transformer to insure adequate analog signal levels at the landward cable terminus. The transducer's 11^{o} beamwidth (relative to the -3 dB levels) allowed sampling footprints no larger than 1.5 m in diameter for water depths of 10 m or less.

A compact shoreline electronics package acquired and recorded analog acoustic signal return-, water temperature- and concrete block tilt-data and allowed acoustic range measurements to be made at selectable time intervals from the returns of individual 68 microsecond pulsed signal transmissions. In the 2004-2005 tests, data on ranges to the ice undersurface were collected at 1 Hz while complete pulse profiles were recorded every 12 s. Signal returns were digitized at 35 kHz and the associated single point ranges and profiles stored together with temperature and tilt data in the SWIPS 69 Mb flash memory. Hydrostatic pressure information was not incorporated into the data stream but was acquired at a separate self-recording gauge mounted next to the SWIPS transducer.

Two types of acoustic data were acquired: corresponding to ranges to the undersurface of the floating ice cover and vertical profiles of backscatter intensity over ranges up to and beyond the latter surface. The range/time delay data were combined with sound speed, water temperature, hydrostatic pressure and air pressure data to produce ice draft time series while the backscattering profiles mapped the strength of scatterers in successive 2.4 cm vertical sections of the water column and in the lower ice cover. The prototype SWIPS was operated continuously from December, 2004 into spring 2005 automatically, switching back and forth between these two modes of operation at operator-selectable intervals. Data periodically downloaded with a laptop computer indicated operational problems to have been confined to occasional interruptions of return signal reception by anchor ice growth on the transducer and its platform prior to the formation of a stable ice cover. At one point this ice growth was sufficient to raise platform buoyancy enough to move the instrument to a new position several m downstream of its original deployment location. Such interruptions ceased to be a problem upon formation in early January of the stable seasonal ice cover which isolated the water column from the cold atmosphere and eliminated supercooling.

Interesting early-season results are presented in Figure 2 corresponding to plots of profiles from 25 consecutive “pings” transmitted at 1s intervals at several successive half hour intervals. The results show both the overhead passages of drifting floes with drafts of a few tenths of m as well as weaker reflections from localized reflectors in the lower portion of the water column. The disappearance of the latter targets with the stabilization of the winter ice cover over the monitoring site shifted the focus of our attention to the latter ice cover itself. Ranging mode data provided a highly detailed depiction of seasonal trends in ice draft which were confirmed by on-ice drilling and sampling programs. Counter-intuitively these data indicated an overall tendency for ice draft to decrease throughout the stabilized ice cover season. Profile data taken during this period (Figure 3) show both the usual absence of water column ice (except for immediately below the ice cover during a March period of exceptionally high river current speeds) and an interesting time dependence of the extent to which returns were received from the interior of the ice cover. In the first instance the water column scatters were identified as clumps of slush ice temporarily dislodged from the lower surface of the ice cover. In the second case, relatively intense returns were being received from the lower portions of the ice which field measurements identified with softer “slush” ice as opposed to the hard “thermal” ice constituent associated with the upper ice layer. In accord with the field data, the extent of penetration strongly suggested that the ratio of slush to thermal components of the ice profile decreased progressively over the course of the winter season (the field-measured and modeled positions of the bottom of the thermal ice layer are indicated in Figure 3) with the slush component disappearing only hour prior to ice break up on April 3.

Three aspects of the 2004-2005 results were cited for attention in further development of SWIPS technology:
1) the avoidance of interruption of early season monitoring by anchor ice production required, as a minimum, inclusion of electrical heating to the underwater package to minimize adhesion to its critical elements;
2) the considerable interest of potential users in early season frazil detection and characterization justified optimization and verification of SWIPS capabilities in this respect;
3) calculations of the extent of acoustic penetration of the ice layer using conventional values for the speed of sound in ice gave unrealistically large depths of penetration. Subsequent field

and laboratory measurements returned speed values much smaller than that of pure ice and, in fact, significantly less than the water value. These lower speed values gave much more reasonable estimates of penetration depth, indicating that this penetration only reached the thermal ice interface late in the ice covered season. Applications of SWIPS technology to detailed characterization of ice cover changes thus require additional quantitative empirical and/or theoretical understandings of sound speed variability in the lower, slush, ice layer.

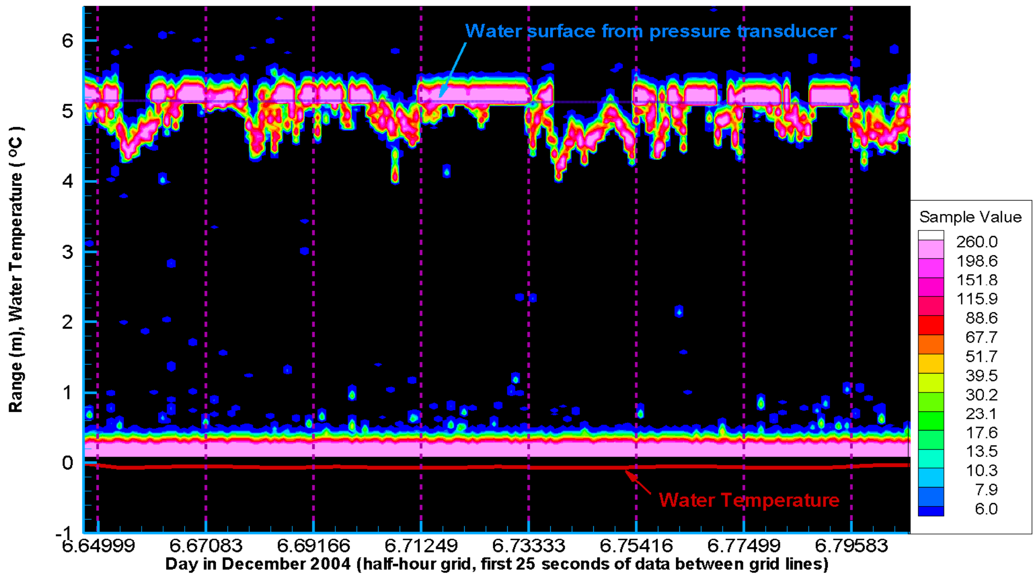

Figure 2 Dec. 6, 2004 SWIPS1 25 1-second resolution profiles are plotted data for successive half hour intervals as denoted by vertical grid lines. Ice floes and frazil point reflectors are evident as are plots of water temperature and water level data.

2005-2006 DEVELOPMENT AND TESTING

Issues 1) and 2) above were addressed in the 2005-2006 field program which deployed two SWIPS instruments operating at different frequencies in adjacent locations at the 2004-2005 deployment site. Progress on the third issue was primarily theoretical and drew heavily on extensions of previous work on sound propagation in mixed media. Progress made on each instance is outlined below and has been incorporated into a new version of the SWIPS instrument to offer more robust monitoring of river and other ice covers as well as of drifting particulate (frazil) ice in their host water columns.

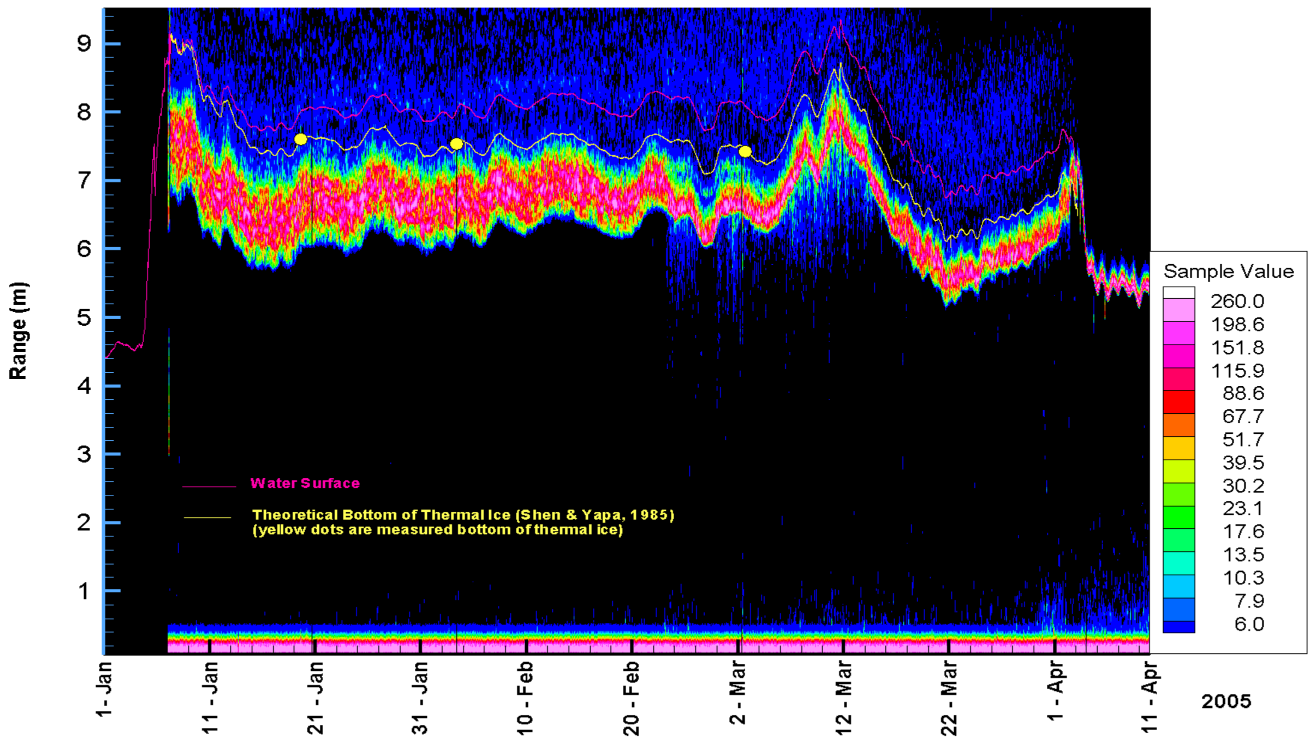

Figure 3 Hourly profiles for mid-winter stationary ice covered period Jan. - Apr. Thermal break-up occurred on Apr. 3. Also shown are local water levels and positions of the modelled, and measured (on 3 dates) bottoms of the thermal ice.

Anchor ice avoidance

Avoidance of anchor ice beam interruptions was addressed by incorporating 100 W heating strips into each of the deployed instruments. In the case of the original, low frequency, unit (SWIPS1) this incorporation consisted of physical attachment to the lower portion of the PVC transducer enclosure. For the new, high frequency, unit (SWIPS2), heating elements were incorporated directly into the potting compound surrounding all but the active face of the transducer. Heating was initiated in early December when water temperatures approached freezing levels. Data downloading on December 14 indicated that heating lowered signal sensitivity and raised noise levels for the SWIPS2 unit. Since these changes disappeared when the heating was turned off, overheating was suspected and the heating effort was abandoned for the SWIPS2 unit. No deleterious heating effects were detected for the SWIPS1 unit, and heating continued to be supplied to this instrument. Consequently, signal return from the SWIPS2 unit began to show the fading signature of anchor ice blockage on January 13 and only began to return, again, gradually with the start of a period of warming water temperatures on January 23. The heated SWIPS1unit on the other hand continued to provide good acoustic data until January 17 when return signal reception ceased abruptly and recorded tilt data indicated that the instrument (and platform) were first turned about 60º from the vertical and, then, completely upside down eliminating meaningful acquisition of SWPS1 data for the remainder of the 2005-2006 program. It was concluded that, while the heater on this instrument allowed four additional days of effective monitoring relative to the unheated SWIPS2 unit and, still, showed no evidence of beam obstruction, buoyancy contributions from anchor ice growth on the support platform and, probably, on the shoreward-directed cable were sufficient to upend the unit. A similar destabilization eventually occurred for the SWIPS2 unit on February 1. In this case, however, the unit was not completely overturned but stabilized (as deduced from the tilt sensor data) with its beam offset by 69ºfrom the vertical. The SWIPS2 sampling parameters were then adjusted (from the shore station) to allow recording of return signals out to the tilt-lengthened range to the river/ice cover surface in order to allow collection of useful data on backscatter from the water column to continue. Tilted beam data associated with the floating ice surface were not of high quality because of the increased specular content of floating ice target returns.

These results indicate that operations of SWIPS units from portable river bottom platforms require external heating to eliminate anchor ice formation both in or adjacent to the sensing transducer and on its support platform to eliminate possibilities for physical destabilization of the instrument. This conclusion has been incorporated into the design of a compact, dense, SWIPS platform with a self-orienting gimbaled transducer mount. Electrical heating and ice-unfriendly surfacing materials preclude ice attachment and distributed weighting is used to minimize chances that drag on buoyant ice-encrusted cables could introduce instrument displacement or misalignment.

Frazil detection and characterization

A major recommendation of Jasek et al. (2005) was that promising but still rather marginal frazil detection capabilities of SWIPS be extended by use of higher acoustic frequencies. This view was based upon the expectation that the signal returns from the water column observed in 2004-2005 were representative of Rayleigh scattering from frazil particles characterized by effective radii, a, satisfying the inequality $2\pi a/\lambda \leq 1$, where λ is the acoustic wavelength in water. Under these circumstances, increases in the acoustic measurement frequency would increase the corresponding cross-sections according to the $1/\lambda^4$ dependence indicated by the Rayleigh theory. Consequently, the SWIPS2 unit was designed to operate at 546 kHz in order to provide a 14.7 dB increase in scattering cross-section relative to the lower frequency used in the SWIPS1 instrument. The effects of this change were very evident in data from the early portion of the 2005-2006 season (i.e. prior to anchor ice complications) as indicated in Figures 4 and 5 for SWIPS1 and SWIPS2 data recorded during the same January time interval. The strength of the SWIPS2 signal, obtained with an intermediate gain setting, provides a good basis for quantitative monitoring of suspended frazil ice populations. The weak, primarily near-bottom, returns received at this instrument (Figure 5) for times earlier than about 07:00 January 12 were typical of the period prior to supercooling of the water column and appeared to be associated with suspended sediments in the lower portion of the water column. The absence equivalent return features in the SWIPS1 record suggests that, in spite of being operated at its highest gain setting, the SWIPS1 instrument was essentially unresponsive to such sediment concentrations. This insensitivity may be a useful property of lower frequency measurements in that it allows distinctions to be made regarding the targets involved in SWIPS2 returns which (Figure 5) show sensitivity to both low-lying suspended sediments and, of course, water column frazil.

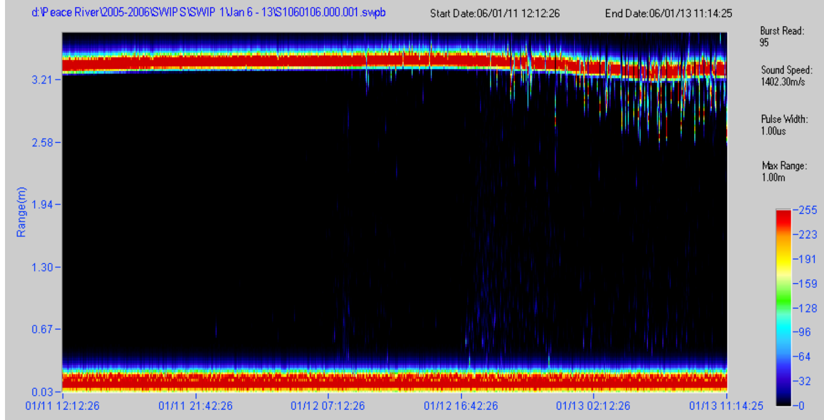

Figure 4: 235 KHz unit data- Initial low frequency results show weak returns from the water column (depths less than 2.94 m) appearing primarily after 18:00 1/12.

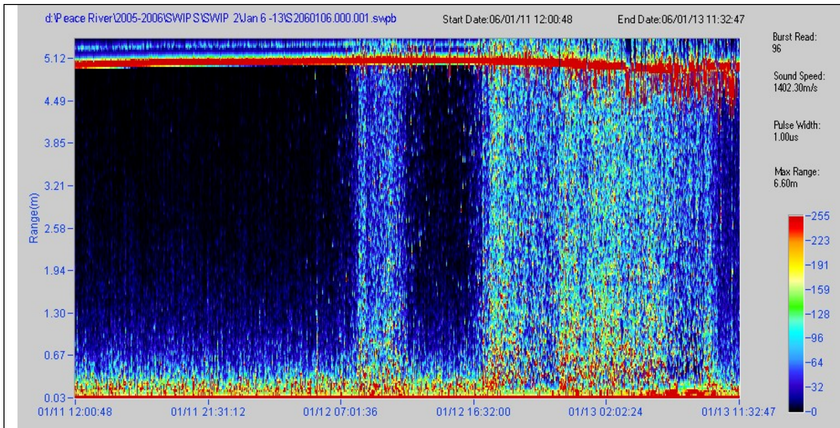

Figure 5: 546 kHz unit data- High frequency results show full range of return variability in same intervals associated with frazil ice presence (depths less than 4.8 m).

Data from common intervals associated with strong frazil-related returns at both instrument sites were used to quantify the relative strengths of the SWIPS1 and SWIPS2 return signals for comparisons with expectations. The comparison process involved use of transmit and receive response and gain parameters intrinsic to the two systems and the expected 14.7 dB difference in Rayleigh scattering cross-sections. Expectations were for SWIPS2 returns 33.6 db larger than those of the SWIPS1 unit. Our measurements found this difference to be 30.7 +/- 3.0 dB, supporting our expectation that the observed frazil returns are interpretable with Rayleigh scattering theory. Since the Rayleigh scattering law begins to break down when $2\pi a/\lambda = 1$, this result suggested that the mean radius of the scattering particles was < 0.4 mm. Using this estimate as an <u>upper</u> limit of the scatterer dimensions in the SWIPS2 measurement, it is possible to interpret the associated 2 m range signal strengths in terms of the Sonar Equation applied to reverberation from volume scatterers to estimate a <u>lower</u> bound of scatterer density (numbers of scatterers/volume). In this approach all scatterers were assumed to be spheres with radii of 0.4mm. The resulting density estimate, n= 1.25×10^{4} scatterers/m^3, is at the lower end of the 10^4 to 10^6 particle/m^3 range of densities given by (Daly et al., 1994) as representative of natural rivers. Actual density values in the middle or upper end of this range were likely to have been obtained if we accounted for the fact that the dimensions of most of the frazil scatterers would have been well below the identified upper limit and, as well, that most of these particles would have been discoidal in shape (Daly et al., 1994) and aligned by the flow to preferentially have their narrowest dimension perpendicular to the vertical SWIPS2 beam. This last difference would also have raised number density estimates from our rough value. Future work towards more quantitative frazil particle density estimation is planned which will involve laboratory flume calibrations and more realistic representations of the distributions of particle size parameters.

Sound Speed in Slush Ice

Potential mechanisms underlying the 2004-5 observations that sound propagates at, very roughly, 1200 m/s in slush ice and shows a weak dependence upon compactness an porosity were reviewed and found to be most consistent with the effects of microbubbles of air in the ice which are driven out of solution as the freezing point is approached from above. The observed speeds were interpretable in terms of the separate properties of water and bubble-infested ice with the resulting sound speed being critically dependent upon the concentration of bubbles with resonant frequencies greater than the acoustic frequency. Although accuracy was hindered by lack of knowledge of the effects of the ice environment on bubble resonance frequency, calculations suggest that such bubbles occupy only about one thousandth of the ice volume fraction occupied by bubbles and that the radii of such bubbles are on the order and less than about 20 microns. It was concluded that the assumption of a 1200 m/s sound speed in the lower portion of the floating ice cover is sufficiently accurate to allow moderately accurate characterization of detected interior features. Improved accuracy and sensitivity in these regards will, however, be obtainable if more detailed field and laboratory studies are carried out on the relationship of sound speed to ice property details.

CONCLUSIONS

With appropriate design modifications and selections, SWIPS instrumentation is capable of continuous operating to provide near-realtime or realtime monitoring of key ice-related parameters in a winter river environment such as: the vertical distribution of suspended frazil and the thickness, composition and stability of moving and stationary ice. The accuracy and extent of detail desired for each of these parameters dictate choices of instrument acoustic frequency and sampling strategies.

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