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ICELAND SPAR AND BIREFRINGENT FILTER DEVELOPMENT

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Birefringent crystals for birefringent filter (BF) are required to provide the necessary linear aperture, wavefront quality, and filter transmission in a given region of the spectrum.

Based on the review of foreign and domestic BF developments, the difficulties in using crystals from known deposits are examined. The Institute of Solar-Terrestrial Physics has developed BFs with extreme characteristics, using an innovative method for enriching crystals from East Siberian deposits and new methods for optical treatment and control of BF elements. We present the characteristics of the filters. Further progress in the creation of BFs in our country depends on the availability of necessary synthetic crystals and natural crystal of Iceland spar, which turned out to be a difficult fate in Russia.

Keywords: birefringent filter, Iceland spar, crystal morphology, optical treatment, solar observations

INTRODUCTION

The high-quality and efficient solar atmosphere fine structure observations made using birefringent filters (BFs) and quickness of their tuning show that BFs can successfully compete with filters of other types, despite costliness and labor inputs required to compose them. The fact that BFs with different characteristics for many spectral lines are still not so popular is perhaps due to the rarity of Iceland spar (optical calcite) in nature and the absence of necessary synthetic crystals. We review the development of the worldwide filter designing that was related to supply of Iceland spar. Achieving extreme spectral characteristics of filters and maintaining the wavefront high quality in known filters on ground- and space-based telescopes depended on the optical homogeneity of crystals of known deposits. On the basis of the review, we analyze why the development of BFs with the aid of Iceland spar has been limited for a long time. The purpose of this work is to show that crystal raw materials of the East Siberian deposits discovered by the expedition “Shpat” and the innovative enrichment technique (instead of splitting crystals into rhombohedrons) significantly expand capabilities of BF production. On the one hand, for the filters with a very narrow passband, which were developed at ISTP together with the staff members of the expedition enrichment shop, crystals were cut, blanks for BF elements were oriented with reference to morphology and growth layers of natural calcite, and the optical homogeneity of the blanks was checked. On the other hand, the optical laboratory of the Institute developed an original technique of precision finishing (optical treatment and simultaneous interference control) of Iceland spar crystal elements. This approach proved to be an important base for composing unique filters for solar observations in the BaII 4554 Å, Hβ, HeI 10830 Å, Hα, and other prognostic lines at ISTP SB RAS. The manufacturing methods described in the review will be useful for developers of new BFs.

Due to the shutdown of natural Iceland spar mining in Russia, we turned to synthetic calcite, whose commercial production was successfully launched in VNIISIMS. Studies at ISTP revealed high optical homogeneity of the obtained samples of synthetic crystals. They are good for making polarizing prisms, but still are small for BFs.

Iceland spar (optical calcite) abroad. First BFs

The beginning of exploitation of Helgustadir (Eastern Iceland) deposit of optical calcite dates back to the middle of the 17th century. Had calcite not broken into rhombohedrons at an angle to its “lucky break” optical axis [Gunter, 2003], centuries could have passed before scientists would have discovered the polarizing properties of light. The first composite polarization prism was invented by Nicol in 1829. [Kristjánsson, 2015].The beginning of crystal optics development can be dated back to 1873, when for the first time in Germany Halle set up special workshops for treating crystals. By the early 20th century, the best part of calcite used for optical studies and instrumentation was apparently obtained from the only quarry in Helgustadir. The reason is the exceptional size of crystals, their chemical purity, and the absence of visible defects. However, from 1873 to 1914, the crystal mining was irregular, causing “hungry” conditions for many scientists and instrument makers who needed this material. New sources of optical crystals in commercial quantities were discovered in southern Africa in the early 1920s shortly after the Iceland government “re-opened” the exhausted quarry Helgustadir for a lot of money. In Europe, a lot of work was put in searching the ways to save crystals when using Iceland spar, and in discovery or invention of its substitutes.

In 1933, Bernard Lyot presented his invention — birefringent filters [Lyot, 1933] that are still an important instrument for solar research. The first Lyot filter was intended to have 9 stages: 10 Glazebrook polarizers and 9 crystal plates of Iceland spar and quartz with ~500 mm total length of Iceland spar optical stack! Despite the small 25 mm clear aperture, the manufacture of the first filter was interrupted in 1934 due to the lack of Iceland spar rhombohedrons required to cut polarizing prisms and plates.

In 1935, Edwin Land invented sheet film Polaroids, which quickly became a commercial product and substituted calcite-based polarizers in most instruments [Land, 1941]. Despite the encouraging results obtained by Lyot with the second filter 36 mm in diameter, the filter had some disadvantages related to the use of Polaroids of that time: low transmission, especially in the blue region of the spectrum, light scattering, and the irregular thickness of the Polaroid films spoiled the quality of solar images. Fortunately, in 1940 and 1941 Lyot obtained two excellent calcite rhombohedrons, and the Polaroids temporarily installed in the 1938 filter were replaced with Abbe's double-beam polarization prisms (calcite—glass) whose calcite consumption was lower than it was required for Glazebrook single-beam prisms. In addition to the main axial beam, Lyot adopted lateral beams at the output of the last Abbe prisms in order to form images of the Sun in other spectral lines.

Within several decades after Lyot performed the theoretical and practical development of BFs, optical companies and physicists at astronomical institutes have created filters similar to the Lyot filter. For narrow-band stages of BFs with high birefringence, Iceland spar is a perfect crystal, but pre-war developments of BF carried out after and simultaneously with Lyot included only quartz stages, whose birefringence is 17 times lower.

The filters were more or less selective, but to get a monochromatic image of the Sun or corona with high spectral and spatial resolution, the amount of high-quality large crystals of Iceland spar was insufficient, although deposits of Iceland spar were discovered in the late 19th and early 20th centuries in the United States (Montana, California), South Africa, India, Australia, Spain, and Argentina. Quartz filters were broad-band, designed for prominence observations. For example, separately from Lyot, Ohman at the Stockholm Observatory proposed a new monochromator in 1938 [Ohman, 1938], which was made by Steeg, Dr., & Reuter, Bad Homburg v.d.H (Germany). In 1939, Zeiss of Jena built two filters. The first one was 13 mm in diameter, with 43 Å full width at half maximum (FWHM) with maximum transparency of 21 %; the second one had 30 mm diameter with 20 Å passband and 30 % transparency [Siedentopf, Wempe, 1940]. In the United States, John Evans created a filter [Evans, 1940] with 20 mm diameter and 5 Å FWHM (manufacturer — Chabot Observatory, USA). At the same time, Edison Pettit built a similar filter equipped with a thermostat and took shots of prominences, using it from May 1941 [Pettit, 1941].

Improved Land polarization films to some extent helped to solve the problem of shortage of Iceland spar for BFs. At the same time, researchers began to use some other polarizing crystals, both natural and artificial, but Iceland spar continued to be in great demand in various optical appliances and remained relevant throughout the 20th century.

By an interesting coincidence, Land, the inventor of polarizing film, partly created this demand and scarcity. When the United States entered World War II, Land invented an optical conoscopic sight [Land, 1945], which consisted of two sheets of polarizing film and two optical wave plates with a plate of Iceland spar crystal inserted between them and cut perpendicular to the optical axis (Figure 1). The sight has no parallax; the interference ring (projectile) displacement on a target depends only on the direction of the (gun) sight and is virtually independent of the shooter's eye position.

These ring sights were used not only during World War II, but later too. The program for military optical sights was launched in the United States in the spring of 1942 after Pearl Harbor. When orders for ORS peaked at 90,000 items in 1943, the demand for 45,000 pounds of optical calcite arose — the unprecedented amount. During World War II, deposits were searched for and exploited quite intensively. Iceland spar became a strategic resource of the U.S. government, which classified studies conducted to estimate Iceland spar reserves in the countries of South and Central America as secret.

Iceland spar requirement for BFs. Filters of the Solar Patrol Service

What amount of Iceland spar is required for BF with 0.5 Å FWHM? Theoretically, to capture an image of the Sun in the Hα line with 1 arc sec resolution, we need a telescope with a ø120 mm lens and a filter with the same diameter mounted in front of the lens, provided that the limit angle of oblique beams passing through the filter is ±0.25° (diameter of the Sun) for a permissible passband displacement of 0.1 of its half-width.

If we use Iceland spar crystals in type I Lyot wide-field stages, we get a 4.4-time increase in the filter field of view [Lyot, 1944]. In this case, the filter can be installed in the reimaging system, in the first approximation its diameter (without the barrel diameter, length of the optical stack, and vignetting) must be not less than 28 mm (120/4.4). To optimally balance the telescope resolution and the installed BF parameters, the condition linking the parameters of the filter and the telescope must be met [Klevtsov, 1984]. For both telecentric and parallel beam path, the relation between the filter parameters and the telescope lens diameter D is defined by the same formula

$$d = D\frac{\omega}{\varepsilon} + \frac{l\varepsilon}{n} \tag{1}$$

or

$$D = \frac{\varepsilon}{\omega}\left(d - \frac{l\varepsilon}{n}\right) \tag{2}$$

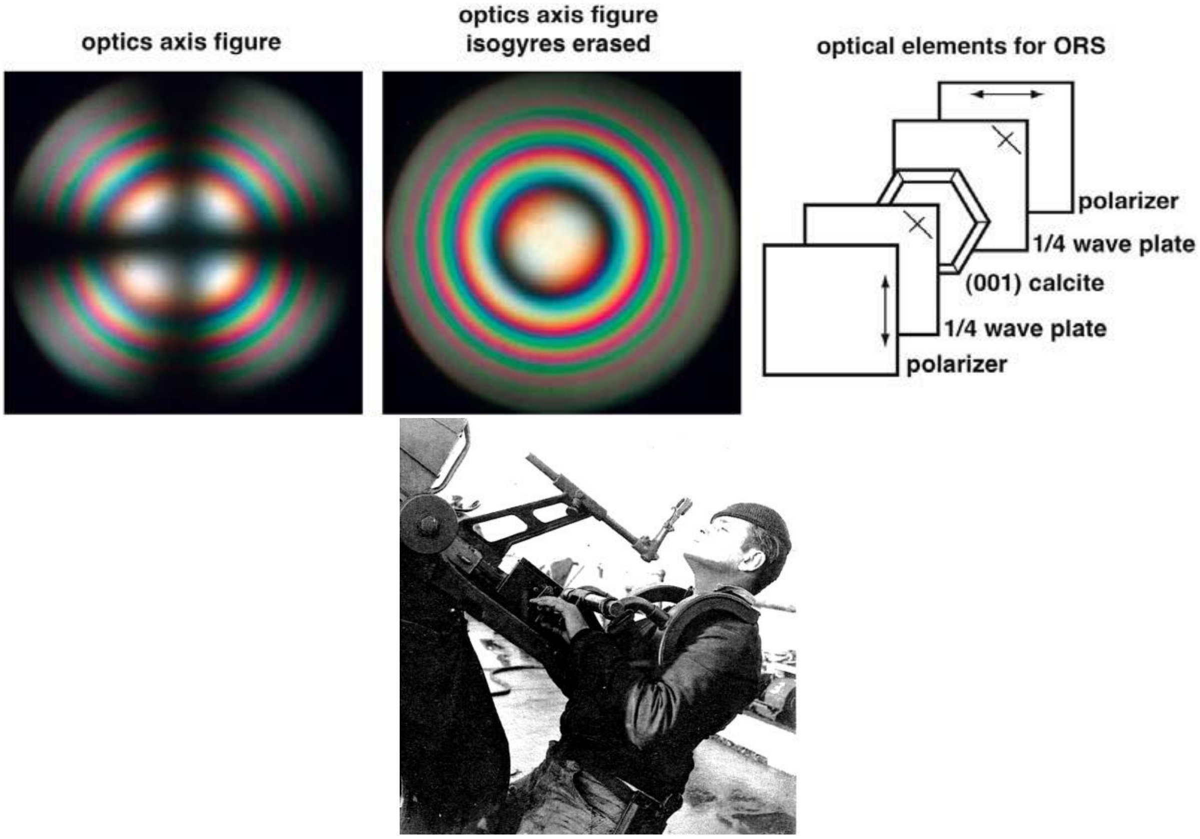

Figure 1. Conoscopic sight (ORS — optical ring sight) and pointing a gun at a target [Gunter, 2003; Orrell, 1995]

where d is the clear aperture, ε is the maximum acceptable angle of incidence on the filter, l is the length of the filter optical stack, n is its average refraction index, ω is the angular non-vignetted field of the telescope. The system focal ratio D/f' must be less than or equal to the filter angular field: $D/f' \le 2\varepsilon$, where f' is the equivalent telescope focus.

Resolution capabilities of both installations are the same, and, if the inclination of field beams does not exceed the maximum angle of incidence ε, we can take it that both provide roughly the same monochromaticity. To improve the resolution capabilities, it is necessary to increase the input window of the filter (diameter of crystals) and to apply a telescope with large objective.

For a 0.5 Å Hα-BF (with film polarizers instead of prisms, with wide-field elements and additional contrast stage), total thickness of Iceland spar crystals must be more than 50 mm. The length of the entire BF stack including film polarizers, calcite, and quartz stages, phase half-wavelength plates, protective glasses, and barrels is about 140 mm. For a telescope with 120 mm lens, when registering the entire solar disk, the clear aperture of a spar crystal filter refined from the formulas above should be about 30 mm. Due to insufficient transmission in the spectrum blue region, some film polarizers in KCaII-BFs are partly replaced with birefringent spar-fused quartz prisms, and the required length of stages from Iceland spar increases to 120 mm.

Iceland spar for foreign BFs could be expected to arrive from the largest deposits discovered in the late 19th and early 20th century in the United States (Montana, California), South African Republic, Mexico, Australia, Argentina, Spain, and later China. The South African fields are now the main base supplying western countries with optical Iceland spar. “Karl Lambrecht Corporation” (Washington, USA) conducts the search, exploration, and exploitation of deposits; it is also involved in treatment of crystals and manufacturing of polarization devices.

In the 1950s, French company O.P.L. made a dozen commercial filters with a 0.75 Å passband. In the 50–60s, B. Halle company (West Berlin) launched serial BF production for the 6563 Å line with a 0.5 Å passband and for the 3933 Å line with a 0.3 Å passband, and offered filters for the 4861 and 10830 Å lines for order. In the 70s, Opton (Carl Zeiss Oberkochen) made a 0.25 Å Hα-filter tunable within ±16 Å, and then a universal filter with 0.25 Å passband scanned within 4200–7000 Å [Skomorovsky, Ioffe, 1980].

Dozens of Halle filters for the Hα and KCaII lines and several Opton Hα-filters were used in the USSR and socialist countries. Over time, crystal elements of most of these filters were repaired and replaced at ISTP. From defects in the periphery of some optical elements of BFs, it was evident that filter manufacturers selected Iceland spar for thick stages of high-order interference with 30–32 mm diameter on the cutting limit of natural crystals. Sometimes, in BFs B. Halle installed crystal elements that should have been rejected in compliance with the manufacturing tolerances [Skomorovsky, Ioffe, 1980].

In the early 80s, a group of Chinese scientists became involved in the “race” of BF development. By this time, their optical and technological base was extensive, rich deposits of optical calcite were discovered in China — all these contributed to the success. In China, filters are produced on a commercial basis at Nanjing Astronomical Instruments Research Center (NAIRC). Several dozen filters have been made, now being used at observatories of China, Korea, and Japan. The Government of China provides considerable budgetary financing of new BF developments for research purposes.

Foreign narrowband BFs with a passband of 0.125 Å and lower

The situation is more difficult with selecting high-quality Iceland spar crystals when making “thick” stages of narrowband birefringent filters. It is also desirable that thick stages have a larger diameter. Conditions (1), (2) take into account the spatial resolution requirements, but they ignore the need to increase the size of the telescope lens (and filter) to alleviate light “starvation” of radiation receivers. This occurs in cases when a narrowband filter provides images of the velocity field and magnetic fields of the Sun with high spatial, spectral, and time resolution when little light passes through the narrow-band filter if the passband is modulated in polarization and velocity. The increase in the lens size (more light caught) results in decreased size of the recorded section of the Sun due to the limited diameter and field of view of the filter. For example, with the Zeiss Oberkochen serial universal filter [Skomorovsky, Ioffe, 1980] (0.25 Å FWHM, ø 36 mm input aperture, ø28 mm output — ±1.6º angular field, 280 mm stack length) installed at the Sacramento Peak Observatory vacuum telescope (ø760 mm entrance pupil), the size of the observed solar surface area by (1), (2) is about 4'. As the filter's clear aperture increases (transverse size of crystals), the recorded area in the Sun increases proportionally at the same spatial resolution.

The need for original BFs has always been really great. Some institutions and scientists developed or continue developing filters with extreme performance for special ground- and space-based telescopes, or improve parameters of the filters made by optical companies. These developments are independent, or performed in cooperation with optical companies.

Australia. In 1961, the National Standards Laboratory (Sydney) made the first Hα-filter with a 1/8 Å passband tunable in a wide range of ±16 Å [Steel et al., 1960]. For a long time, experimenters believed that the 1/8 Å passband was limiting for a birefringent filter made of Iceland spar until SibIZMIR made a 0.08 Å ultra-narrow BF in 1973 from crystals mined by the “Shpat” expedition.

USA. At Sacramento Peak Observatory, the all-band filter was implemented in practice on the basis of a 0.25 Å Opton tunable Hα-filter, which was supplemented with a tunable wide-angle 0.125 Å achromatic stage made of Iceland spar. In cooperation with the firm, Beckers upgraded the filter: an additional element from Iceland spar was installed in order to narrow the passband down to 0.125 Å (Hα) [Beckers et al., 1975]. To maintain the observed field of view of 4' when the extended stack was used, a 0.017 Å increase instead of the 0.012 Å one was allowed in the passband spectral displacement for oblique beams.

In 1976, BFs for space missions were enhanced in Lockheed Research Laboratory (Palo Alto, California). A model of 0.1 Å filter was constructed for trials of the filter sample at the space observatory on Spacelab 2. Based on the model, they constructed the flight version of the solar polarimeter (SOUP) in a spectral region 4000—7600 Å with a 0.05 Å passband at λ5250 Å, for magnetic field measurements [Title, 1976].

France. A Lyot-type monochromator was constructed at Meudon Observatory to get two-dimensional images and measure magnetic fields and velocities [Dollfus et al., 1985]. The instrument is fully tunable, 0.121 Å (λ5250 Å) FWHM, with high transmission in a spectral range from 5000 to 6700 Å.

China. The Solar Magnetism and Activity Telescope (SMAT) is installed at the Huairou Solar Observing Station (HSOS). The instrument consists of two telescopes, which respectively measure the complete magnetic field vector and perform full-disk Hα-observations. The magnetograph contains BF, λ_c5324.19 Å, 0.1 Å FWHM, 37 mm clear aperture [Hong-Oi Zhang et al., 2007].

Study of the influence of Iceland spar quality on parameters of narrowband BFs

Developers of non-standard narrowband filters were short of high-quality crystals, they faced the need to overcome the impact of their optical inhomogeneity on optical and spectral characteristics of the filters.

With a 1/8 Å tunable Hα-filter [Steel et al., 1960, Bray, 1977] (Figure 2), manufactured in the National Standards Laboratory (Sydney, Australia), due to the filter’s narrow passband quite a few pioneering studies have been carried out on the fine structure and motions in the solar chromosphere. The authors thought that owing to insufficient sizes of the available Iceland spar crystals it was unlikely that a narrower passband could be achieved with BFs of this type. The interferograms, taken from the said work (Figure 3), of optical quality of one of the calcite elements 35 mm in diameter and 46.4 mm thick show that inhomogeneous crystals were used to make thick elements of this filter. As demonstrated below, these inhomogeneities were caused by the impossibility of correct orientation of blanks relative to growth layers in the crystals cut into rhombohedrons.

To improve the filter’s spectral characteristics, the surface of thick elements was figured in a way to smooth the curvature of the interference bands of uniform birefringence. The element spectral characteristics got better, but since all elements including those with the figured surface were dipped into immersion to reduce Fresnel reflections, wavefront distortions appeared in the optical stack, which resulted in lower image quality [Bray, Winter, 1970].

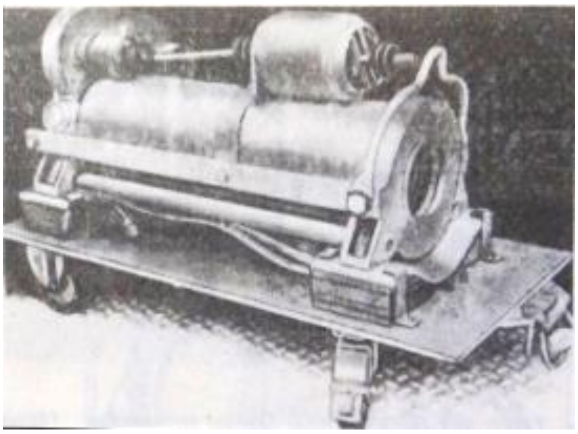

Figure 2. 1/8 Å BF

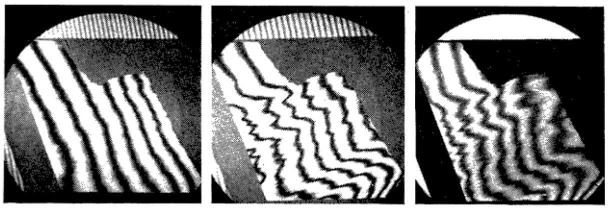

Figure 3. Interferograms: ordinary ray (*a*), extraordinary ray (*b*), interference bands of uniform birefringence — difference between o- and e-ray paths(*c*)

Figure 4 shows a filter for Spacelab [Title, 1976] and its laboratory fore-runner LAPPU filter (Lockheed Alternative partial polarizer universal filter) that were constructed by A. Title. These are tunable interference-polarization filters with partial polarizers to increase transmission. Each filter has a ~0.1 Å passband and a 35 mm aperture. In the LAPPU filter, all elements are made of calcite; its total length is 179 mm. The thinnest 1.4 mm element is not wide-angle; the thickest one is 81.7 mm in total.

However, for the thickest elements the size and homogeneity of calcite crystals were not sufficient. Local figuring through optical polishing was required to compensate for minor calcite inhomogeneities and to ensure 33 mm final aperture of the filter. Interferograms in Figure 5 from [Title, 1976] indicate that the optical stack of the filter introduces curvature and astigmatism of about 2λ. These defects were reduced by installing the filter on the telescope in an f/30 beam at a 15 cm distance from the focal plane: changes in the focus caused by wavefront distortions are less than one-tenth of the diffraction-limited depth of field.

Figure 4. Prototype of a 0.1 Å flight filter for Spacelab 2 (left) and a LAPPU filter (right)

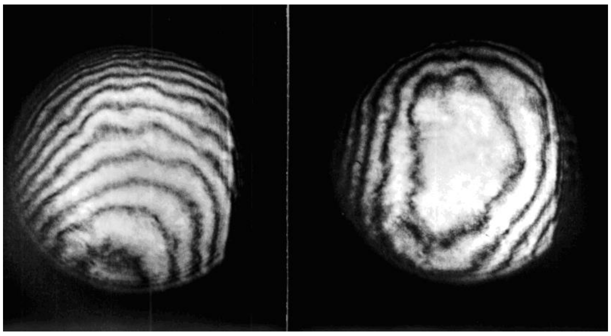

Figure 5. Interferograms of the LAPPU filter wavefront

There are a few more of the known BF developments whose aperture remained within 35 mm because high-quality calcite suitable for filters was hard to find.

French polarimeter [Dollfus, Moity, 1993] at Meudon Observatory has almost the same parameters as the monochromator [Dollfus et al., 1985]. Spectral resolution of 45000 (or 013 Å in λ 5800 Å), 0.033 rad aperture, 20 % transparency, tuning from 5000 Å to 6700 Å. Diameter of the filter (crystals) is 32 mm. To make two calcite plates, 29.12 and 58.40 mm, large natural crystals were thoroughly selected based on birefringence uniformity.

Nevertheless, local figuring of the plate surfaces was required later (during polishing) to obtain uniform birefringence throughout the 32 mm linear field of view.

To measure the full magnetic field vector with the T2 telescope [Ueno et al., 2004] of the four-tube Solar Magnetic Activity Research Telescope (SMART) of the Hide Observatory, researchers of Nanjing Institute of Astronomical Optics and Technology of the Academy of Sciences of China (NIAOT, former NAIRC) developed a Lyot filter with 0.125 Å FWHM at λ6302 Å with 50 mm (!!!) aperture, the largest in the world. The filter elements are made of crystals possibly derived from the Guizhou deposit (China). Spatial resolution of vector magnetograms turned out to be not so high as it was expected for a telescope with large aperture. We think that unacceptable aberrations of the Lyot filter were the source of the problems. After the filter was repaired, its linear field of view was limited to 30 mm!

The forced use of inhomogeneous crystal blanks by BF developers, as shown below, was caused by insufficient awareness of crystal formation, kinetics of their layer growth, and methods for assessing the quality of optical crystals for BFs among Iceland spar suppliers. Clean, without cracks, areas were determined visually; and they were selected by **chipping out rhombohedrons** from natural crystals with a chisel (Figure 6). The splits often passed through a homogeneous monoregion of the crystal, and its dimensions turned out to be small even in large rhombohedrons.

This form of cutting, which is not at all favorable for manufacturing crystal elements of BFs, existed in all countries for many years. In Russia in the 60s, an end was put to this barbaric enrichment technique because of which consumers in turn when cutting out polarizing optics from rhombohedrons sent a lot of optical material to waste.

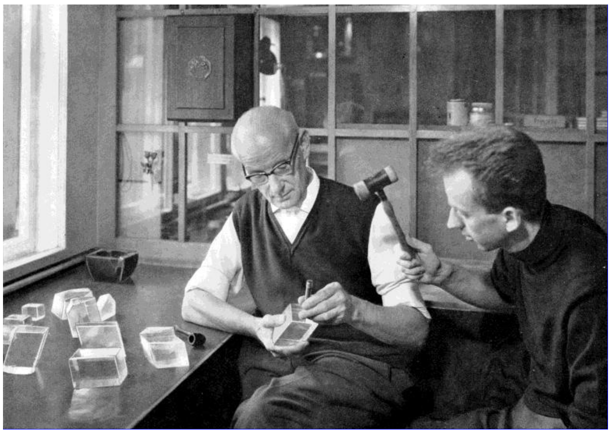

Figure 6. Technicians are cleaving Iceland spar crystals. A photo of 1863–72 from the anniversary booklet "90 Years in the Service of Optics", published by *B. Halle Nachf.* in 1963 [90 Jahre im Dienste der Optik,1963]

Iceland spar and first BF developments in Russia

The occurrence of Iceland spar in Russia has been noted long ago. There are known deposits in Yakutia, in the region of Crimea, in Tuva, in the Caucasus. However, no workable deposits could be found for a long time. Focused geological exploration eventually led to a number of discoveries in the Nizhnyaya Tunguska Basin. Expedition "Shpat" of the VPO "Soyuzkvartz-samotsvety" of the Ministry of Geology of the USSR explored deposits and mined mineral raw materials. In 1926—1946, deposits in the lava region trap and highly valuable deposit of Dzhekinde in the tufa region were proved to be of commercial value. The latter produced a significant amount of Iceland spar that supplied the demand of the optical industry for several years ahead [Serykh, Frolov, 2007].

Before commercial exploitation of Iceland spar deposits began, this unique mineral was primarily used in production of optical polarizing prisms for microscopes. The first signal for a serious "jerk" to search, explore, and extract the mineral was crystals of Iceland spar found in the sighting system (see Figure 1) of the Messerschmitt fighter captured at the beginning of the Great Patriotic War. The deposits were studied and exploited quite intensively during the Great Patriotic War. However, there was no solid mineral and raw material base with balance reserves or inferred resources of Iceland spar.

In the early 50s, due to the intense development of the optical-mechanical industry of the USSR, the need for Iceland spar increased and its production ramped up. The industry imposed strict requirements to the quality of optical calcite for transmission, scattering, and optical homogeneity. The weight of some extracted crystals sometimes reached tens and hundreds of kilograms, but it was possible to obtain far less optical material of good quality. Crystals may partially deteriorate when "soft" shocks (explosions) are applied during their extraction from solid basalt rocks or due to temperature difference when rapidly brought to surface from the frozen soft tufa rocks. Spar crystals extracted from the subsoil are nothing more than raw materials for further enrichment. In Tungus expedition, calcite was at first enriched by a very wasteful traditional method: crystals were broken into defect-free rhombohedrons, using a hammer and a chisel (Figure 6).

Despite the presence of crystals in the Shpat expedition, it suddenly appeared that in the 50s in optical-mechanical enterprises there was an opinion that optical calcite was absent in the country. This was most likely due to the wartime classification of deposit reserves, and GOSPLAN was not aware of availability of the crystals. Accordingly, the industry was targeted at purchasing spar from abroad [Serykh, Frolov, 2007], replacing spar with polaroids; and, if it was impossible to use them due to poor quality, at taking the appliances out of production. Geologists had to visit the State Optical Institute (GOI), the Leningrad Optical Mechanical Association (LOMO) many times and to make contacts with other enterprises in order to provide steady supply of optical raw materials [http://forum.web.ru/ viewtopic.php?f=24&t=4544&start=0&sid=f100c7021833f2267b7fd7df58057b23 26].

Due to the expansion of exploration works since the 1960s, the mineral resource base of optical calcite was created. This covered the needs of the USSR optical and mechanical industry in full, as measured for the period from 1960 to 1991. An enrichment shop was built in the settlement of Tura. Crystals were delivered there from all deposits, and it was possible to assess the crystals and deposits without sending crystals to the central shop in Moscow, as was done before. In the "Shpat" expedition, an enrichment technique was developed and introduced. It was based on sawing crystals into pinacoid plates (oriented perpendicular to the optical axis), decrypting their internal structure, and cutting into optically-oriented blanks of specified sizes and quality. The main contribution to the development and introduction of the enrichment technology was made by D.Sc. in Geology in Mineralogy Skropyshev A.V., Cand.Sc. in Geology in Mineralogy A.V. Shustov, Head of the "Shpat" Expedition Zolotukhin I.A., Head of Shop A.L. Kukui, Chief Mechanician of the expedition V.A. Tsvetkov. The introduction of this technique instead of crystal cleavage increased the output of optical calcite from the raw spar 2–3 times and allowed suppliers to make the switch to deliveries of ***optical part blanks to consumers instead of cleavage rhombohedrons***.

In the USSR, BF designs were developed off the bitten line, almost in isolation from western scientists and companies who promoted scientific and production contacts with each other. In 1949, the first USSR BF with quartz stages was successfully employed at the Crimean Observatory to study solar prominences [Severny, Gilvarg, 1949]. In the following years, a unique BF with Iceland spar crystals was created at GOI according to calculations and methodology by S.B. Ioffe [Ioffe et al., 1950]. At that time, the filter had the narrowest passband of 0.6 Å. It was successfully tested at Pulkovo. Then under the leadership of S.B. Ioffe in GOI, BFs for different (strong) lines of the chromosphere and corona were made [Vinogradova et al., 1989]; industrial manufacture of Hα-filters was launched at LOMO. By the beginning of the International Geophysical Year (1957), the network of the national Solar Patrol Service stations was equipped with special chromospheric telescopes with BF-1 for the Hα line with 0.6 Å FWHM. Optical diameter of the filters was 28 mm.

In the 80s, a new 0.5 Å filter BF-6 with wide-angle thermally-compensated stages, tunable within ±1 Å [Vinogradova, Kuznetsov, 1986] was developed at GOI and LOMO (availability of good crystals facilitated the development). Some observatories received filters, but due to slow production and long-running finishing BF-6 never took on the market of astronomical equipment.

Production of BFs was stopped in Russia. Unfortunately, within ten years the BF dichroic polarizers failed due to the solar beam impact. Later, the same thing happened to the Halle filters. There arose a risk that the network of Solar Patrol Service disappears in the USSR.

Filter developments at ISTP. Features of crystal selection and technological processes of their treatment and control

The great need to repair LOMO and Halle BFs, the demand for specialized narrowband filters (and, of course, the initiative and support of Director V.E. Stepanov) prompted the organization of optical laboratory and development of new BF solutions and large-size optics at the Institute of Solar-Terrestrial Physics (former SibIZMIR) in the early 60s [Skomorovsky et al., 2013]. Before LOMO established a site for BF-1 upgrading (new name BF-4), the ISTP SB RAS optical laboratory repaired these filters and, as already said, replaced the out-of-operation polarizers and crystal elements of Iceland spar in Halle and Opton filters for the Hα и KCaII lines. At that time, crystals for filter repair in the form of cleavage rhombohedrons (practically without controlling their optical quality) were purchased from the Centralized Moscow shop of the “Shpat” expedition.

Enthusiasts of the new crystal enrichment technology in the northern settlement of Tura (Evenkiya) considered it important that the entire economic cycle from the search and development of deposits to the supply of end products would be provided by one manufacturer (expedition "Shpat"), interested in the rational use and minimization of waste of valuable crystals. It was planned to create an optical shop for manufacturing and delivering polarizing optics to customers. The "Shpat" expedition was also interested in collaborating with ISTP opticians in developing a technique for selecting blanks for BFs and assessing their optical quality with an interferometer (Figure 7).

The possibility of getting high-quality Iceland spar blanks of large size laid the groundwork for the development at ISTP of two-band BFs with large aperture and high transmittance for the prognostically important spectral lines of barium Ba II 4554 Å and hydrogen Hβ, with FWHM 0.08 Å and 0.09 Å respectively. The design length of the entire optical stack made only of Iceland spar crystals (birefringent elements and polarization prisms) with the 40 mm aperture was 320 mm. The production of the optical stack of the filter should involve careful selection of blanks used to make filter elements of a given thickness with precise alignment of the optical axis.

Selection of blanks. Single crystals include various growth pyramids, which are parts of crystals formed by parallel layers occurring when one face of the crystal is moving during growth (Figure 8). When growth conditions change, the refraction index and content of impurities in the crystal may change.

After a preliminary inspection, crystals of deposits Krutoye, Babkinskoye, Polydzhikit, Razlom (Figure 9), etc., which contained high-quality raw materials, are sawed perpendicular to the optical axis into pinacoid plates with defect-free areas of maximum dimensions in the shop on a machines with diamond disks.

Pyramids and layers of growth become visible after acid etching of plates (Figure 10) or after polishing their surfaces and viewing the volumetric and surface luminescence of the plates under ultraviolet light through the UFS-1 light filter.

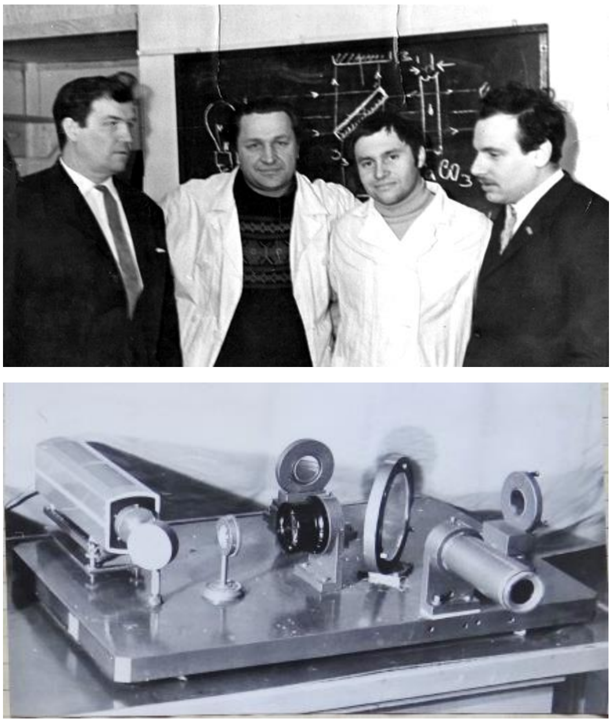

Figure 7. Enrichment shop of the “Shpat” expedition: Head of the expedition I.A. Zolotukhin, main mechanician V.A. Tsvetkov, mineralogist A.V. Shustov, Chief of the ISTP SB RAS Laboratory V.I. Skomorovsky (*a*); Twyman interferometer installed by ISTP opticians in the enrichment shop (*b*)

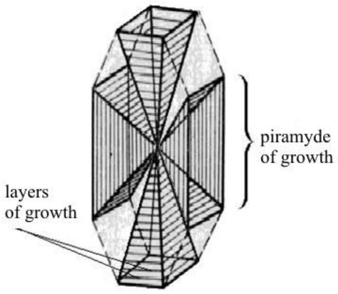

Figure 8. Schematic drawing of crystal growth

Figure 9. Crystals from the Razlom deposit (Irkutsk Region). The optical axis in the crystals is vertical

Figure 10. Pyramids and layers of growth — etch patterns on a plate of Iceland spar (optical axis is perpendicular to the plane of the Figure)

Boundaries of growth pyramids are clarified by the value of laser beam light scattering inside the plate, which also depends on the peculiarities of the pyramid (Figure 11). We cut the plates to obtain the largest blanks for BF elements from one growth pyramid, taking the responsibility for the defective zone permissible size.

Measurements we made at the shop, using the Twyman interferometer, confirmed the high optical homogeneity the piramid of the cleavage rhombohedron [Skropyshev, Kukui, 1973]. This homogeneity was within $1 \cdot 10^{-6}$, almost the same in all directions. Therefore, in blanks from this pyramid without growth layers detected, the working direction of a beam was chosen perpendicular to the main optical crystal axis along the pyramid largest dimension. This direction often did not coincide with the other symmetry axes used to orient a crystal on the X-ray goniometer, but retained the valuable raw material. The calcite blanks cut from other growth pyramids often reveal a stratified structure. This posed difficulties in making Australian 1/8 Å BF with a 1/8 Å passband (see Figure 4). Sometimes, refraction indices in the layers of one growth pyramid and in different pyramids differ by $5 \cdot 10^{-5}$.

Figure 11. Optician estimates light scattering inside a plate

To enhance optical quality of the BF element blanks made of plates with growth layers, we sawed the plates parallel to the main optical axis along the normal to the growth layers. [Shustov et al., 1970]. Then, a light beam passed through the filter perpendicular to the growth layers. The influence of growth layers is shown in the image (Figure 12) obtained with the Twyman interferometer [Kushtal, Skomorovsky, 2002]. Homogeneity of an oriented workpiece, especially by birefringence (see Figure 3), has no abrupt jumps across the field of view. Blanks with local inhomogeneities that distort the birefringence interference bands by no more than 1/10 of a fringe we therefore considered to be acceptable for BF manufacturing.

Of course, with our interferometric selection, the “grade” of unique blanks of Iceland spar and their price had been rising. And it made benefits to the SparShpat expedition. Nonetheless, the main reason why the expedition staff provided their help was their desire to retain raw materials for unique developments, not to “butcher them” to make relatively small polarizing prisms and light separating elements, orders for which were to increasingly received by the expedition from optical and electronic industries. The Head of the enrichment shop of the expedition A.L Kukui informed ISTP SB RAS about the possible output of large homogeneous Iceland spar blanks for the filters developed.

Precise orientation of BF elements

The octahedron shape of BF crystal elements is convenient for their mutual orientation at an angle of ±45° (Figure 13). Blanks are cut from pinacoid plates regardless of other crystallographic axes of the plate in order to cut out the maximum size of the elements. Since it is

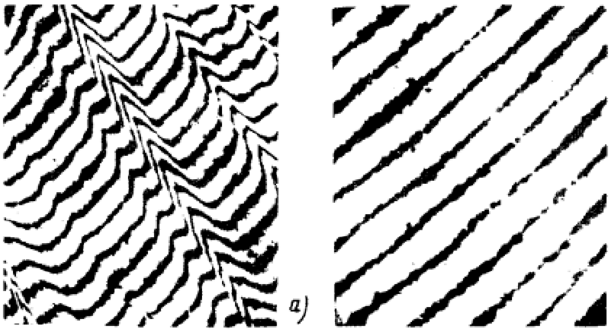

Figure 12. Homogeneity of a crystal workpiece: not oriented (*a*); oriented relative to the growth layers (*b*)

difficult to use the X-ray goniometer in this case, an optical conoscope [Domyshev et al., 1989] was engineered for precise orientation of the BF element working surfaces to the main optical axis (Figure 14). The crystal element is installed on the conoscope's stage representing a slightly scattering transparent plate. It is illuminated by a parallel beam of monochromatic light from a point light source (laser). The conoscopic pattern is formed by the plate-scattered light; and the luminous point image is formed by a parallel beam passing through the plate. The crystal element surfaces are processed until the beating of the conoscopic pattern relative to the unmoved image of the luminous point of the source is eliminated during the rotation of the stage. The table itself is set up once through the absence of a beating of the auto-collimation image obtained from the back polished side of the scattering plate of the table. Measurement accuracy is ~1′, practically not subject to instrumental error.

Optical treatment of BF elements. Oriented BF elements are finished in thickness, flatness, and plane-parallelism through optical polishing. In total, changing the thickness of the element in accordance with the tolerances for these three parameters should not shift channel spectrum fringe of the element by more than one tenth of the bandwidth (0.36 μm for 6563 Å) [Giovanelli, Jefferies, 1954]. The element thickness is finished by alternate machine polishing of their flat surfaces with simultaneous interferometric control of flatness and plane-parallelism. Expansion coefficients of Iceland spar crystals are different along the optical axis and perpendicular to it. It is therefore important that optical polishing does not cause temperature difference between the lower, treated, and upper free surfaces. It is the temperature gradient rather than the anisotropy of mechanical properties that leads to the astigmatic curvature of the treated surface. ISTP SB RAS developed instruments, modes of BF element precision treatment with an optical machine-tool, and an interferometer with a wedge crystal plate to test optical thickness of the treated plate relative to the reference one located directly in the operating area of the machine-tool (Figure 15) [Domyshev et al., 1981].

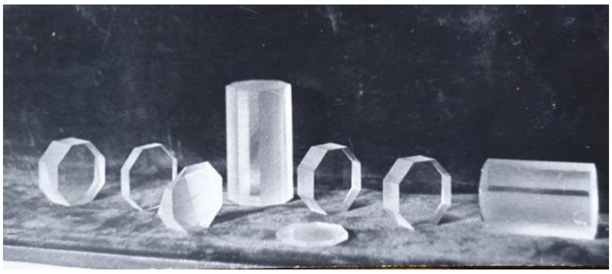

Figure 13. BF crystal elements from Iceland spar

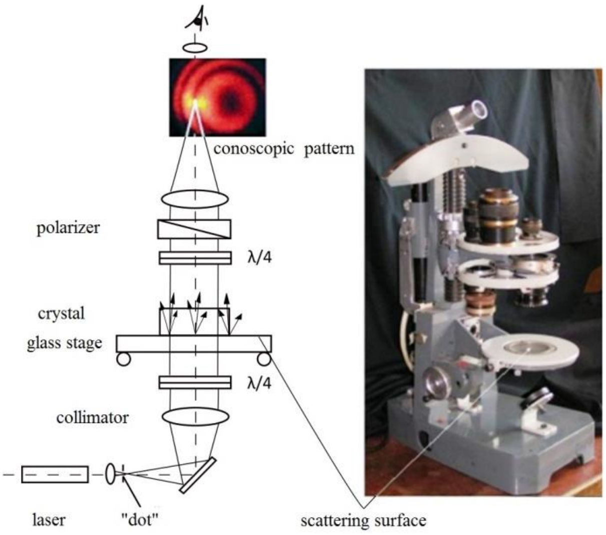

Figure 14. Conoscope

Double-sided treatment — simultaneous optical polishing with a machine of both sides of a large number of crystal elements with the same thickness — also represents a precision method of finishing. (Figure 16). The process ensures plane-parallelism of the elements and the absence of thermal deformations as there is no temperature difference between the surfaces. We developed tools, found processing modes, and were the first in our country to adapt this method for double-sided optical treatment of BF elements — quartz quarter-wavelength and half-wavelength plates [Domyshev et al., 1976]. This process can be successfully applied to finishing of Iceland spar elements in mass production of Lyot-type BFs, or a single Solc filter containing dozens of identical elements.

Figure 15. Machine-tool with interferometer for plate finishing

Figure 16. Double-sided optical polishing of elements

BF developments. Availability of Iceland spar crystals mined and enriched in the "Shpat" expedition, thorough selection of homogeneous blanks by ISTP opticians, new techniques of crystal element treatment and testing made it possible to develop narrowband BFs for studying the fine structure, velocity field, and magnetic fields at different levels of the solar atmosphere.

In 1973, two-band BF for the BaII 4554 Å (0.08 Å passband) and Hβ 4861 Å (0.09 Å passband) lines was put into operation [Alexandrovich et al., 1975, Kushtal, Skomorovsky, 2002]. It was tunable within the width of spectral lines. By its characteristics, IPF was one of the most successful developments in the practice of filter engineering and is still a unique instrument.

The filter aperture is 40 mm, the length of the entire optical stack made of quartz and Iceland spar crystals is 430 mm, the length of the spar part only (spar-glass STK-3 prisms and birefringent elements) is 320 mm. Interferograms (Figure 17) indicate that the optical homogeneity of the entire crystal stack is within $1/4\lambda$, which far exceeds, for example, that in the LAPPU filter (see Figure 5).

Two-band BF for the BaII 4554 Å and Hβ 4861 Å lines was installed in the Solar Non-Eclipse Coronagraph (BVK1) of the Sayan Solar Observatory (Figure 18).

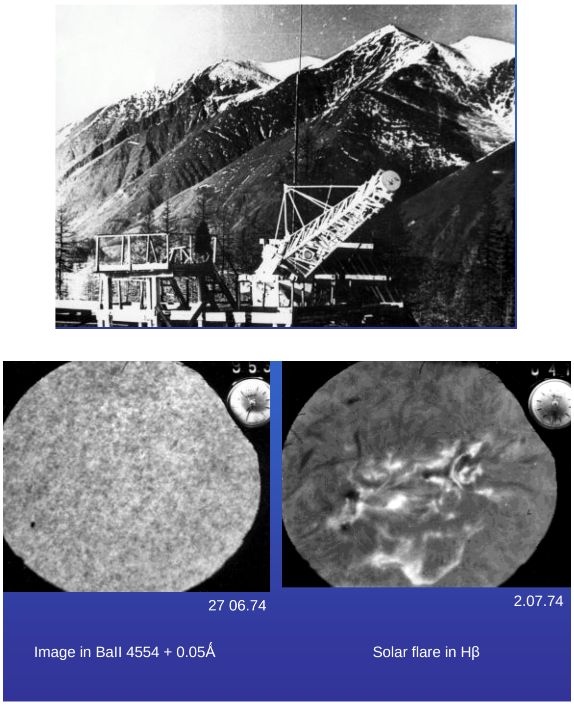

Figure 17. BVK1 of the Sayan Observatory and filtergrams in the BaII 4554+0/005 Å and Hβ lines

Figure 18. Homogeneity of the filter optical stack for the line BaII 4554Å and Hβ 4861Å

A long-term series of observations and studies of the fine structure and wave processes in the middle and upper atmosphere of the Sun have been carried out with this filter. To illustrate the instrument operation, Figure 17 shows photos, taken by V.I. Skomorovsky, of the solar surface region in the wing of the barium +0.05 Å line and in the center of the hydrogen line (frame-by-frame camera RFK-5, 35 mm film, type 17, 0.1 s exposure).

In accordance with the Agreement on Scientific Cooperation between the University of Utrecht (Netherlands) and ISTP SB RAS about the filter installation and joint observations at the Dutch Open Telescope DOT, preliminary test observations were carried out at the Swedish Vacuum Solar Telescope (Figures 19, 20) in La Palma. In 2000, a large number of frames were obtained in the center and in the wings of the barium line for further processing of images of the Sun. Figure 21 shows the speckle-reconstructed images in the wings of the ±0.05 Å line and a dopplerogram [Sütterlin et al., 2001]. The observations demonstrated that the Ba II 4554 Å line is a superior diagnostician of Doppler velocities, and the filter optical quality meets the diffraction resolution requirement for a given field of view of the telescope. Currently, BF is installed on the Dutch Open Telescope (Figure 22) in a multi-channel filter system to study the fine structure, velocities, and magnetic fields in the solar atmosphere [Hammerschlag et al., 2010].

Figure 19. Swedish Vacuum Solar Telescope (SVST)

Figure 20. Russian observers with BF at SVST

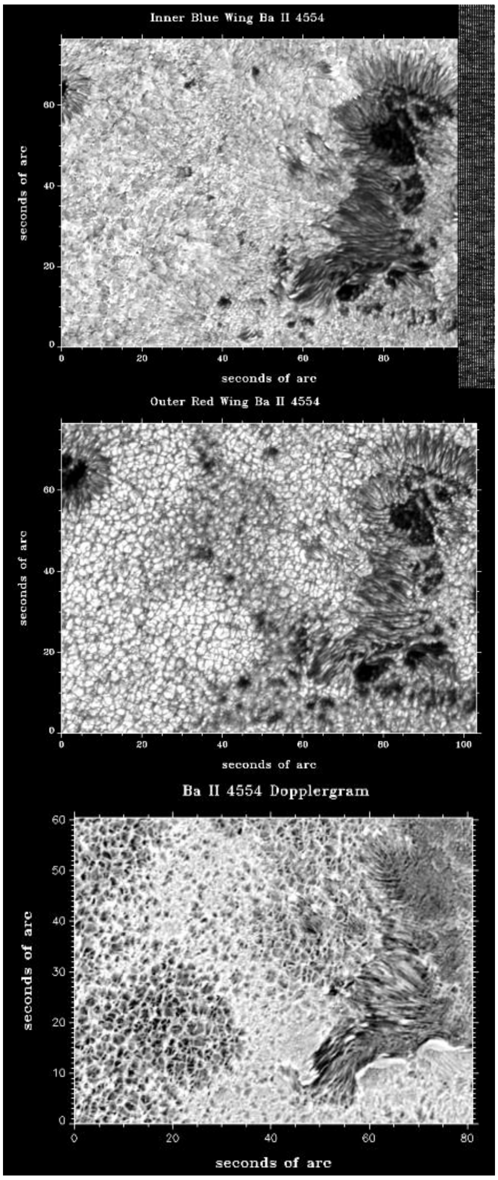

Figure 21. Images in the blue and red barium wings (*a*, *b*). Each image results from combining of about 100 frames obtained with a 0.2 s exposure. Dopplerogram (*c*)

Two-band tunable BF for the prognostically important chromospheric lines HeI 10830 Å and Hα 6563 Å [Kushtal, Skomorovsky, 2000, Domyshev, et al. 2004] (full width at half maximum is 0.46 Å and 0.23 Å respectively) was manufactured at ISTP SB RAS in 1997 (Figure 23).

Despite significant progress in the development of BFs abroad, there were no efforts successful enough to create a filter operating in the visible and IR ranges simultaneously. In order to tune the filter to other interesting spectral lines by changing the temperature, all elements of the filter, except for quarter- and half-wavelength plates, are made of one material — optical calcite (Iceland spar).

This BF at the Large Solar Non-Eclipse Coronagraph (BVK-2) can be used to make spectral and filter observations at a time. Figure 24 presents a filtergram of an active region in the center of the helium line. The thin vertical white line is the spectrograph's slit.

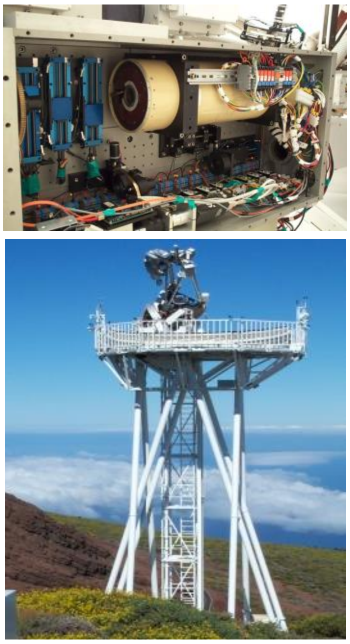

Figure 22. Filter for the BaII 4554 Å and Hβ 4861 Å lines installed at DOT

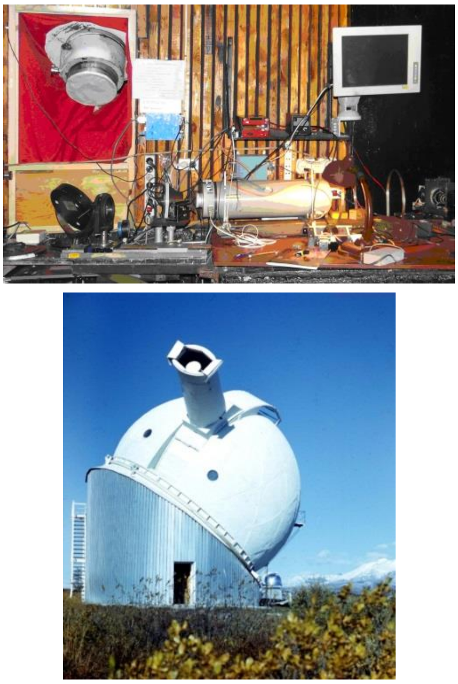

Figure 23. BF in the helium and hydrogen lines at BVK

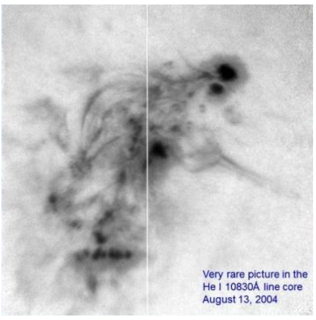

Figure 24. AR in the He I 10830 Å line core

Over the years, ISTP SB RAS has delivered other solutions, using large crystal blanks of Iceland spar.

- BF (0.6 Å passband) for the corona red line was successfully tested at the Large Solar Non-Eclipse Coronagraph of the Sayan Observatory and then used for observations at the coronagraph of the Abastumani Observatory [Khetsuriani et al., 1989].
- An Hα-filter (0.38 Å passband) was designed and manufactured for a finder of the Solar Synoptic Telescope (SOLSIT), [Lopteva et al., 2018].
- Failed BF calcite elements of the Baikal Astrophysical Observatory's Hα-telescope were replaced [Skomorovsky et al., 2016].

A filter for the FeI 6173 line designed for magnetic field measurements is currently under construction. It includes a narrowband polarization filter-modulator (0.06 Å passband, 42 mm clear aperture and a preliminary Solc filter. It is the first time when both filters contain elements of negative (Iceland spar) and positive (paratellurite) crystals [Skomorovsky et al., 2012].

The use of crystals of different sings makes it possible to increase the angular field of the filter and save Iceland spar.

Making these instruments, we have emptied our "strategic" stock of large blanks of natural Iceland spar for further developments. For the "Shpat" expedition, the 60–80s were the most favorable and effective in geological studies of Iceland spar deposits and the mineral mining in our country. This period coincided with intense scientific development and increased attention of the government to remote underdeveloped regions of the country. However, due to the deep crisis in the Russian industry, consumption of optical raw materials dropped. In the 90s, there occurred a disparity between energy prices, mining equipment, transportation services, on the one hand, and prices for minerals, on the other hand. This led to the fact that under the new economic conditions, a significant part of the explored reserves passed to the unprofitable category. In 2001, funding of Iceland spar exploration and mining was completely unwound.

SYNTHETIC ICELAND SPAR

Back in the 1960s, when the world saw some lower availability of natural calcite, it became important to grow it. For calcite crystals, the popular method of melt growing is not suitable, as calcite decomposes at high temperatures. The most promising method is the hydrothermal technique — growing crystals in a homogeneous medium of calcite solution at high pressure but relatively low temperatures under conditions most closely resembling the natural growth of crystals [Ikornikova, Butuzov, 1956]. Iceland spar is one of the most recent products of the natural hydrothermal process [Eremin, 2004]; it crystallized in open rock cavities at temperatures from 180 to 400ºC under pressure up to a few MPa. Therefore, growing at temperatures far from the melting point contributes to the formation of low-stress crystals, and hence optically homogeneous.

This method of growing calcite crystals was used in the USSR [Ikornikova, 1975], the USA [Kinloch et al., 1974], France [Gener et al., 1974], and Japan [Kikuta, Hirano, 1990]. But the technique of commercial seed growing of calcite crystals in an autoclave with solution for the first time ever was developed at the All-Union Institute of Synthesis of Mineral Raw Materials (VNIISIMS) by the senior researcher Yu.V. Pogodin [Pogodin, Dronov, 1972] and developed by his followers [Lyutin et al., 1980].

Solution compositions were found in which spontaneous crystallization was suppressed, and calcite has a positive solubility coefficient. Therefore, the synthesis of crystals is carried out at direct temperature drops. The charge made from fragments of natural crystals is loaded into the dissolution zone (lower part of the autoclave), and seed plates cut from large crystals of natural Icelandic spar are loaded into the crystallization zone (upper part of the autoclave). Due to ther-mal convection created by distributed heaters (ΔT = 5–10 °C), the saturated solution moves from the higher temperature lower dissolution zone to the lower temperature upper crystallization zone. Due to the supersaturation of the solution at the temperature of the crystallization zone, an excess of dissolved CaCO3 is deposited on the seeds. The duration of crystallization cycles varied with-in 20–250 days, temperature 200–400º C, pressure 10–150 MPa. (~100-1500 tech. atm.).

Calcite single crystals were grown in VNIISIMS under hydrothermal conditions on the oriented seed crystals parallel to prism faces (1120). Their optical inhomogeneities related to refraction indices were examined at ISTP SB RAS, using the Twyman interferometer [Borodin et al., 1985]. Crystals of this orientation are very profitable to manufacture BF plates. To exclude the surface shape effects on optical homogeneity measurements, surfaces of a 60×34×8 mm crystal were treated within 0.2λ. Then, flat glasses producing distortions no more than 0.05λ were superimposed on the surfaces through immersion oil (n_d =1.57). Figure 25, *a* presents a wavefront interferogram of synthetic calcite in *e*-ray. Measurements indicate that optical inhomogeneities in the refraction index in a sample 7 mm thick are no more than $3 \cdot 10^{-6}$.

The ordinary and extraordinary ray wavefront difference is shown in the interferogram (Figure 25, *b*) obtained with the sample installed with the quartz wedge between parallel polarizers in one arm of the interferometer, while the second was closed. The direction of the sample optical axis was 45º to the axes of polarizers. It is this scheme that BF elements work in. It can be seen that a crystal can provide homogeneity of the filter spectral band by birefringence no worse than 0.1λ. No striae and bubble inclusions are detected from the shadow picture in this sample.

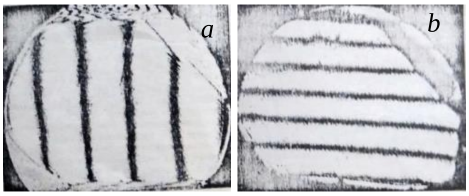

Figure 25. Interferograms of synthetic calcite in double path of the *e*-ray wavefront (*a*), the difference between e- and o-ray wavefronts (*b*)

Thus, in terms of quality synthetic crystals with reasonably large dimensions could replace natural calcite whose best samples do not exceed 60×60 mm. Should these developments be introduced into industry, severity of the calcite problem could have been settled.

There is no doubt that research into calcite crystal growth is an important topic, and the hydrothermal technique remains one of the most promising methods for growing high-quality calcite crystals in a homogeneous medium at high pressures and relatively low temperatures. For example, at the Moscow Polytechnic University [Nefedova, 2016] the synthesis process has been implemented at temperatures about 260°–270° and pressure P=70 MPa. As a result of 30 to 140 daily synthesis cycles in the presence of different impurities, the possibility of commercial growing of optical calcite single crystals on seed crystals that were parallel to natural faces (habitus) was confirmed. Dimensions of synthetic single crystals (Figure 26) are suitable for manufacturing different optical prisms of 10 to 20 mm in size, but unfortunately insufficient to manufacture BF elements.

Currently, Crystaltechno Ltd. [http://crystaltechno.com] offers synthetic single-crystal Iceland spar in the form of pinacoid plates with 10–50 mm clear aperture, 2–8 mm thick.

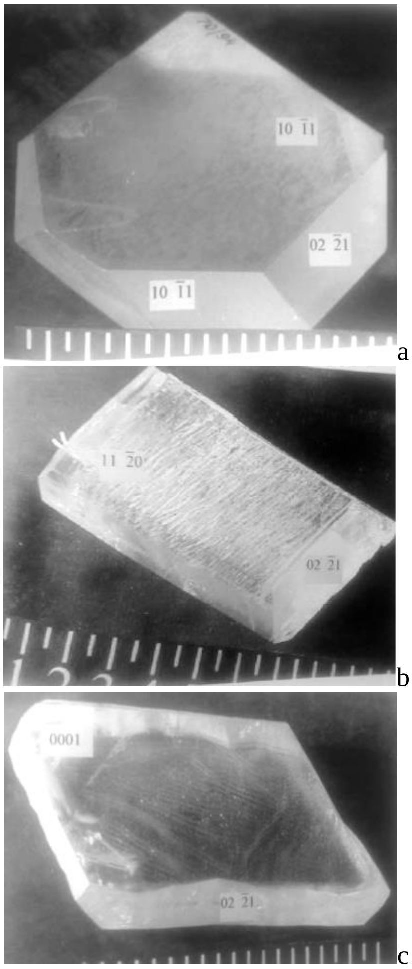

Figure 26. Crystals are grown on seed crystals cut from natural or synthetic calcite parallel to the faces of natural growth: parallel to the cleavage rhombohedron (*a*); parallel to the optical axis (*b*); perpendicular to the optical axis (*c*)

CONCLUSION

Iceland spar is a sunstone. Way back, vikings, the seafarers, used it to find direction to the Sun hidden in clouds and to determine their location. Due to to Iceland spar, important scientific discoveries were made; polarizing prisms and narrowband filters were invented. Classical BF may contain crystal plates of Iceland spar (polarizing stages, birefringent or polarizing prisms) 30–45 mm in diameter, total length 100–300 mm or more. BF capabilities are determined by the quality of optical crystals and technological progress in creating filters. Scientific institutions (and industry) in different countries took their own ways to develop modern BFs. The filter aperture depended on the availability of Iceland spar, whose source for Western developers could be mines in Mexico, South Africa, India, and possibly in the United States. Harry Ramsey (Lockheed) investigated and evaluated samples of South African calcite supplied by Karl Lambrecht company. He believed that if high-quality calcite exists, there is no reason to search for alternative materials, and developers of filters who want to obtain samples for clear aperture of 50 mm and more should have sufficient knowledge about calcite and work closely with mine owners [Title, Rosenberg, 1979].

This is the path that Russian BF developers took, and owing to cooperation between ISTP SB RAS and the "Shpat" expedition, unique narrowband filters were created for observations of processes on the Sun. At the same time, ISTP SB RAS developed tools and technological procedures for precision treatment and control of crystal plates. Developments of machine-tools for Double-sided optical treatment and finishing of crystal plates with simultaneous control of their parameters were passed for introduction over to enterprises of optical and mechanical industry of the USSR: LOMO (Leningrad), BelOMO (Minsk), LZOS (Lytkarino, Moscow region), MONOCRYSTAL (Kharkiv).

In 1970, for the discovery of Iceland spar deposits and provision of the national industry with optical raw materials, the crew of the Geological and Exploration Expedition “Shpat” was awarded with the State Prize of the USSR: the loss of precious mineral was minimized, consumers began to receive not “raw” material, but blanks from which it was possible to manufacture prisms at lower expenses. However, the need of domestic industry for Iceland spar in the post-perestroika period significantly decreased, and the Federal Agency on subsoil use declared that further development of raw material base for Iceland spar was not feasible. Due to the fact that the “Shpat” expedition conducted not only exploration but mining too, the latter is completely abandoned. In Russia there is no close prospect that any Iceland spar blanks can be got from the explored deposits. Funding of scientific institutions that are interested in calcite is far deficient to revive the industry. The sunstone still sits somewhere in the Evenkian taiga.

Currently, due to many factors, developed countries have stopped commercial production of BFs. China, the Nanjing Institute of Astronomical Optics and Technology (NIAOT) of the Chinese Academy of Sciences, is the only filter supplier in the world. In China, filters are manufactured on a commercial basis owing to the high technological level achieved and rich Iceland spar deposit discovered in Guizhou Province. The Government of China provides considerable budgetary funding of new BF developments for research purposes. In the US, developers of tunable BF for corona studies in emission lines within 500—1100 nm (the filter FWHM is 0.5 Å at ~600 nm) at the largest coronagraph in the world with 1.5 m aperture [Tomczyk, 2016] think of the use of synthetic crystals along with Iceland spar: lithium niobate, paratellurite, KDP, magnesium fluoride, etc. The criterion of crystal applicability for BF polarizing stages is their light efficiency (étendue — a product of clear aperture and field of view), which should not reduce the telescope efficiency. For the filter with a specified passband, application of lithium niobate is considered the most effective for the 2° field of view if one accepts that it is possible to grow homogeneous crystals with 100 mm clear aperture compared to natural Iceland spar crystals, which sometimes were available in diameter under to 60 mm. Spar crystals are more effective in narrowband filters for investigating the fine structure with high spectral resolution in a small field of view.

There is no hope for large crystals of artificial spar yet, but there is hope for natural large crystals. Only how to get them in Russia?

Restoration of the Solar Patrol Service network equipped with modern telescopes with BFs is being discussed in Russia. We believe that in order to carry out developments for the Solar Service, as well as to create focal instruments (narrow-band monochromatic filters) of the KST-3 Large Solar Telescope, crystals of Iceland spar are needed, the “competitors” of which are under development.

Developmental trends are that BFs should provide the automated Solar Patrol Service with high spatial, temporal resolution, and informativeness, and be a major tool in solar studies. This is confirmed by the described BF developments in the USA, China, France, and Germany. Dozens of instruments, which use high-quality spar, are installed at western observatories and in spacecraft.

The difficulty in creating essential BFs in Russia is not that the country lacks optical calcite, but that the optical industry yet refuses to accept orders from the Russian observatories. It is probably necessary to complete the commercial chain so that enrichment (mining) of raw materials is associated with the sale of unique products if their production is sufficient. We hope that the situation with scientific instrumentation in the country will turn to the best, and the raw material base should be ready for this. It is possible that mining of Iceland spar and high technologies for BF manufacture will be restored in Russia.

We are grateful to Head of the expedition “Shpat” I.A. Zolotukhin for the invitation to participate in selection of Iceland spar blanks for BFs, to Cand. S. in Geology and Mineralogy A.V. Shustov and main mechanician of the expedition enrichment shop V.A. Tsvetkov — their knowledge of crystal morphology and enrichment technology facilitated the successful development of the filters. We greatly appreciate the helpful discussions provided by Dr. Joseph M. Kats.

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